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Formation of the typology for the evaluation of the sustainability of nearly zero energy ports

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"Be hungry for success, hungry to make your mark, hungry to be seen and to be heard and to have an effect. And as you move up and become successful, make sure also to be hungry for helping others."

Εγώ, ο Σηφάκης Νικόλαος του Γεωργίου, δηλώνω υπεύθυνα ότι:

1) Είμαι ο κάτοχος των πνευματικών δικαιωμάτων της πρωτότυπης αυτής εργασίας και από όσο γνωρίζω η εργασία μου δε συκοφαντεί πρόσωπα, ούτε προσβάλει τα πνευματικά δικαιώματα τρίτων.
2) Αποδέχομαι ότι το Πολυτεχνείο Κρήτης μπορεί, χωρίς να αλλάξει το περιεχόμενο της εργασίας μου, να τη διαθέσει, μετά το πέρας 24 μηνών από την αρχική υποβολή, σε ηλεκτρονική μορφή μέσα από τη ψηφιακή βιβλιοθήκη του, να την αντιγράψει σε οποιοδήποτε μέσο ή/και σε οποιοδήποτε μορφότυπο καθώς και να κρατά περισσότερα από ένα αντίγραφα για λόγους συντήρησης και ασφάλειας.

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Περίληψη

Τα λιμάνια χρησιμεύουν ως κρίσιμοι κόμβοι για τη μεταφορά υλικών, επιβατών, αυτοκινήτων και εμπορευματοκιβωτίων, καθιστώντας τους ενεργοβόρους καταναλωτές που βασίζονται κυρίως σε ορυκτά καύσιμα. Κατά συνέπεια, αποτελούν σημαντική πηγή ατμοσφαιρικής ρύπανσης, ιδίως όσον αφορά τις εκπομπές αερίων του θερμοκηπίου. Η αντιμετώπιση του φαινομένου της κλιματικής αλλαγής αποδεικνύεται κορυφαία προτεραιότητα για τους λιμένες, οι οποίοι προσανατολίζονται στην αύξηση της ενεργειακής τους απόδοσης και στην μείωση του περιβαλλοντικού τους αποτυπώματος. Η αυξανόμενη πρόοδος προς πιο βιώσιμες υποδομές επέστησε την προσοχή των λιμενικών αρχών προς ενεργειακά ζητήματα. Ως αποτέλεσμα, οι λιμένες τείνουν να προσπαθούν να εκμεταλλευτούν έξυπνα συστήματα διαχείρισης ενέργειας, συστήματα ανανεώσιμων πηγών ενέργειας και συστήματα αποθήκευσης ενέργειας για να ενσωματώσουν τη βιωσιμότητα και να αυξήσουν την αποδοτικότητα των λειτουργιών τους.

Η παρούσα διατριβή προσπαθεί να καλύψει τα ερευνητικά κενά σχετικά με τη βιωσιμότητα που σχετίζεται με τα λιμάνια, δημιουργώντας μια απαρέγκλιτη και αξιόπιστη τυπολογία που αποτελείται από τα ακόλουθα:

- Μια ολοκληρωμένη βιβλιογραφική μελέτη κι ανασκόπηση για την βελτίωση της κατανόησης της βιωσιμότητας των λιμένων και για την δημιουργία βάσης πληροφοριών για τις υπάρχουσες τεχνολογίες και μεθοδολογίες,

- Χρήση μοντέλων/εργαλείων μηχανικής μάθησης και νευρωνικών δικτύων για την πρόβλεψη του ενεργειακού προφίλ των λιμένων για το 2030, τονίζοντας την ανάγκη βελτίωσης της υπάρχουσας κατάστασης των λιμένων από πλευράς ενέργειας,

- Δημιουργία ενός έξυπνου συστήματος ελέγχου εξωτερικού φωτισμού για τον βέλτιστο έλεγχο της παροχής φωτισμού με βάση τη φωτεινότητα του ήλιου και τη χωρητικότητα του κάθε χωρίου του υπό εξέταση λιμένα, συμπεριλαμβανομένων μη επεμβατικών συστημάτων διαχείρισης έξυπνων ενεργειών στις λιμενικές δραστηριότητες,

- Δημιουργία διάφορων Υβριδικών Συστημάτων Ανανεώσιμων Πηγών Ενέργειας για κάθε περίπτωση λιμένα με την ταυτόχρονη προσομοίωση, συζήτηση και σύγκριση των αποτελεσμάτων τους. Η αξιολόγηση του κάθε συστήματος οδηγεί στην επιλογή του βέλτιστου ικανοποιώντας τα τρία κριτήρια της βιώσιμης ανάπτυξης,

- Ενσωμάτωση και μοντελοποίηση της τεχνολογίας του «cold-ironing» για τη μείωση των εκπομπών από τα αγκυροβολημένα πλοία σύμφωνα με την πλέον πρόσφατη νομοθεσία της Ευρωπαϊκής Ένωσης. Ταυτόχρονα, η σκοπιμότητα της συμπερίληψης ενός συστήματος αποθήκευσης ενέργειας με υδρογόνο αξιολογείται ως προς την αυτονομία και τη μείωση των εκπομπών αερίου θερμοκηπίου του λιμένα.

- Τέλος, η δημιουργία ενός εφαρμοσμένου συστήματος διαμοιρασμού της ενέργειας αποσκοπεί στον έλεγχο ενός υβριδικού συστήματος ανανεώσιμων πηγών ενέργειας στους λιμένες, διασφαλίζοντας τη λειτουργική σταθερότητα και ασφάλεια.

Εν κατακλείδι, η έννοια του σχεδόν μηδενικού ενεργειακού λιμένα προωθεί μια ελκυστική υποδομή που χρησιμοποιεί σχεδόν εξ'ολοκλήρου πράσινη ενέργεια με αποτέλεσμα ένα μηδενικού περιβαλλοντικό αποτύπωμα, συμβάλοντας καθοριστικά στον μετριασμό της κλιματικής αλλαγής. Η κυκλική οικονομία θα επωφεληθεί από τη μετατόπιση ενέργειας από μηχανές εσωτερικής καύσης σε Συστήματα Ανανεώσιμων Πηγών Ενέργειας, η οποία θα βελτιώσει τη συμβίωση μεταξύ λιμένων και των γειτονικών τους πόλεων. Ένα καθαρότερο μέλλον για τον τομέα της κινητικότητας είναι επικείμενο μέσω της ιδέας του λιμένα σχεδόν μηδενικής κατανάλωσης, το οποίο ενισχύει τα έξυπνα συστήματα διαχείρισης ενέργειας. Ενδεικτικά, τα προτεινόμενα Υβριδικά Συστήματα Ανανεώσιμων Πηγών Ενέργειας, σε συνεργασία με τα έξυπνα συστήματα διαχείρισης ενέργειας, επιτυγχάνουν σχεδόν μηδενικές εκπομπές, οδηγώντας σε μια οικονομικά εφικτή επένδυση όσον αφορά την βιωσιμότητα, αυξάνοντας ταυτόχρονα την ασφάλεια του εφοδιασμού των υπηρεσιών του λιμένα μέσω της 24ωρης αυτονομίας. Έχει επισημανθεί η αναγκαιότητα μετατροπής των λιμένων σε καινοτόμες και ενεργειακά αποδοτικές υποδομές, υποδεικνύοντας τον κρίσιμο ρόλο τους στην παγκόσμια κλιματική αλλαγή.

Abstract

Ports serve as crucial hubs for transporting materials, passengers, cars, and cargo, making them high-energy consumers that rely primarily on fossil fuels. Accordingly, they are an important source of air pollution, particularly in terms of greenhouse gas emissions. Climate change mitigation is turning out to be a top priority for ports, which work to increase their energy efficiency and diminish their carbon footprint. The increasing progress toward more sustainable infrastructures has drawn the attention of port management authorities to energy issues. As a result, ports are taking advantage of smart energy management systems, renewable energy systems, and energy storage systems to incorporate sustainability and enhance the efficiency of their operations.

This thesis attempts to fill the research gaps on port-related sustainability by creating a solid and reliable typology that consists of the following:

- A comprehensive literature study is done to improve understanding of port sustainability and provide a foundation of information about existing technologies and methodologies;
- Several machine learning models/tools were used to forecast the ports' energy profile for 2030, highlighting the need to improve the existing status of the ports in terms of energy;
- A Smart Outdoor Lighting Control System was created for optimal control of the lighting output of the new luminaires based on the illuminance of the sun and the space occupancy of each port, including a non-invasive Smart Energy Management Systems into port activities;
- Several Hybrid Renewable Energy Systems for each port case are conceptualised, simulated, discussed, compared, and evaluated to pick the optimal among them by satisfying the three sustainability criteria;
- Cold-ironing technology is being integrated and tested to reduce emissions from berthing ships according to the most recent European Union laws. Simultaneously, the feasibility of including a hydrogen storage system is assessed in terms of autonomy and reducing the port's Green House Gas emissions.
- Finally, an applied evaluation framework is created to give insights into the design, size, and control of a Hybrid Renewable Energy System in seaports, guaranteeing operational stability and safety.

Concluding, the nearly Zero Energy Port concept promotes an attractive infrastructure that uses almost explicitly green energy resulting in a zero-carbon footprint and providing a crucial contribution to climate change mitigation. The circular economy will benefit from the energy shift from fossil-fuel energy producers to Renewable Energy Systems, which will improve cohabitation between ports and port towns. A cleaner future for the mobility sector is imminent through the nearly Zero Energy Port concept, which Smart Energy Management Systems like the proposed one strengthens. Indicatively the proposed Hybrid Renewable Energy Systems, in cooperation with the suggested Smart Energy Management Systems operation, achieve almost zero emissions, leading to an economically feasible investment towards sustainability, concurrently enhancing the port's services safety-of-supply through the 24-h autonomy. The necessity of ports' transformation into innovative and energy-efficient infrastructures has been highlighted, indicating their critical role in global climate change.

Publications

The following articles have been published in peer-reviewed scientific journals in the context of this doctoral Thesis:

Publications in scientific journals directly related to the PhD thesis

- Sifakis N, Tsoutsos T. Nearly Zero Energy Ports: A necessity or a green upgrade? IOP Conf Ser Earth Environ Sci 2020; 410:012037. https://doi.org/10.1088/1755-1315/410/1/012037.
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- Sifakis N, Kouletakis K, Tsoutsos T. Forecasting a port's energy demand for 2030 on the base of nearly Zero Energy Ports concept, 2021[Will be submitted]

Publications in scientific journals indirectly related to the PhD thesis

- Sifakis N, Savvakis N, Daras T, Tsoutsos T. Analysis of the Energy Consumption Behavior of European RES Cooperative Members. Energies 2019; 12:970. https://doi.org/10.3390/en12060970.1
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Publications in international scientific conferences

- Sifakis N, Theocharis T.1st PhD candidates conference TUC, Dec. 18 Sifakis N, Tsoutsos T. Decarbonisation of ports and tourist cities, towards sustainable development, Blue Growth, Heraklion Crete, January 2019
- Sifakis N, Mavroudis O, Tsoutsos T. Evaluating the prospect of nearly Zero Energy Ports, DPMCO, Athens, May 2019
- Argyriou I, Sifakis N, Tsoutsos T. What measures are needed to improve the sustainability of the Mediterranean ports from the stakeholder's viewpoint: A case study of Souda port, Chania, Crete, EiNT, Sep 2019
- Sifakis N, Tsoutsos T. Nearly Zero Energy Ports: A necessity or a green upgrade? SBE19, Thessaloniki, Oct. 2019 Sifakis N, Theocharis T. 2nd PhD candidates conference TUC, Dec. 19
- Vichos E, Sifakis N, Tsoutsos, T. Challenges Of Nearly Zero Energy Ports: An Essential Or An Ambition?, 9th Global Conference on Global Warming (GCGW-2021), August 1-4, 2021,Virtual conference [upcoming]
- Sifakis N, Savvakis N, Daras T, Tsoutsos T. Sustainable Urban Energy Systems Conference, November 2018, Delft (Netherlands) : Renewable Energy Cooperatives as prosumers, results from the REScoop plus project Sifakis N, Savvakis N, Daras T, Tsoutsos The European experience from the operation of the Energy Communities. The Experience of the program RESCOOP PLUS, Social Entrepreneurship Forum 2018, Athens, 23-25 November 2018
- Aryblia M, Sifakis N, Tournaki S, Tsoutsos T. Mitigating climate change through the monitoring of the urban environment in a touristic Mediterranean city, 9th IWACP, May 2020
- Theocharis Tsoutsos, Maria Aryblia, Nikos Sifakis, Stavroula Tournaki Monitoring and Assessment of The Urban Environment in A Touristic Mediterranean City, ECOMM, 2020

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Nomenclature

Artificial Intelligence	AI	International Maritime Organization	IMO
Artificial Neural Networks	ANN	Lead Acid Battery	LA
Autoregressive Integrated Moving Average	ARIMA	Levelized Cost of Energy	LCOE
Backpropagation	BP	Life Cycle Analysis	LCA
Box-Jenkins ARIMA Model	SARIMA	Light Emitting Diode	LED
Capital Recovery Factor	CRF	Li-Ion Battery	LI
Carbon Footprint	CF	Linear Regression	LR
Cold Ironing	CI	Liquefied Natural Gas	LNG
Cycle Charging	CC	Load Following	LF
Daily Artificial Neural Network	D-ANN	Machine Learning	ML
Daily Linear Regression Model	D-LR	Mean Squared Error	MSE
Daily Machine Learning Model	D-ML	Monthly Artificial Neural Network	M-ANN
Decomposition Method Model	DM	Monthly Linear Regression Model	M-LR
Depth of Discharge	DoD	Monthly Machine Learning Model	M-ML
Digital Addressable Lighting Interface	DALI	National Aeronautics and Space Administration	NASA
Ecological Footprint	EF	National Renewable Energy Laboratory	NREL
Electrolyzer	El	nearly Zero Energy Port	nZEP
Emission Control Area	ECA	Net Grid Purchases	GP
Energy Efficiency	EE	Net Metering	NM
Energy Management System	EMS	Net Present Cost	NPC
Energy Storage System	ESS	Payback Period	PP
European Commission	EC	Peak Shaving	PS
European Sea Port Organization	ESPO	Photovoltaic System	PV
European Union	EU	Port Container Terminal	PCT
Fuel Cell	FC	Prediction of Worldwide Energy Resources	POWER
Gaussian Process Regression	GPR	Renewable Energy Systems	RES
Global Warming Potential	GWP	Renewable Energy	RE
Green House Gas Emissions	GHGs	Return on Investment	ROI
Gross Domestic Product	GDP	Root Mean Squared Error	RMSE
Heating, Ventilation, and Air Conditioning	HVAC	Rubber Tired Gantry	RTG
Hourly Artificial Neural Network	H-ANN	Smart Energy Management Systems	SEMS
Hourly Linear Regression Model	H-LR	Smart Outdoor Lighting Control System	SOLCS
Hybrid Optimization of Multiple Energy Resources	HOMER	Standard Test Conditions	STC
Hybrid Renewable Energy System	HRES	Strengths, Weaknesses, Opportunities, and Threats Analysis	SWOT
Hydrogen Tank	HT	Support Vector Machines	SVM
Initial Capital	IC	Time-of-Use	TOU
Institute of Electrical and Electronics Engineers	IEEE	Vanadium Redox Flow Battery	VRFB
Intergovernmental Panel on Climate Change	IPCC	Web Of Science	WOS
Internal Rate of Return	IRR	Wind Turbine	WT
International Electrotechnical Commission	IES		

1 Introduction

1.1. The beginning of the contemporary ecological crisis

In recent decades, an ever-increasing ecological crisis has occurred on the planet. This crisis started first at a local level, and then, with the start of the industrial revolution and the vast use of fossil fuels, it expanded on a global scale. From the very beginning, when the prospects of fossil fuels were perceived, their value skyrocketed and immediately became a commodity of direct or indirect use. Thanks to this discovery, houses were electrified, everyday goods are produced in bulk, and the distance between continents became a matter of days. The result of this influence is that each country's economic growth, prosperity and power are inherently linked to them. The abuse of their availability at the expense of the environment leads to exponential negative impacts over time. These impacts range from softer, such as worsening local health, to irreparable destruction of whole ecosystems and the energy crisis that has arisen [1].

1.2. Understanding the energy problem

The current energy crisis is of high importance for global authorities, being a matter-to-be-solved. The reason that fossil fuels became so popular from the very beginning was their high calorific power, namely the large amounts of energy stored in small volumes of fuel, and their accessibility because single drilling gives access to millions of tons of fuel with an uninterrupted flow. Moreover, their extensive use for mass production of goods, electricity, transport, heating, etc., proves that they are the driving force behind modern society. On the other hand, however, they have some significant disadvantages, which, because of their wide application scale, have caused irreparable problems in the society and environment. In particular, they are divided into three broad categories[2]:

- The various emitted air pollutants like CO_2, NO_x,SO_2, etc., are released not only during the combustion for energy production, but also during the extraction, and transformation processes and the transitional transport before their final destination;
- The dependence on their use. Fossil fuels account for more than 75% of global power generation, as well as for the vast majority of the global transportation sector;
- Their finite nature, which is the most remarkable. Fossil fuels are finite and are estimated to be near their complete depletion; the transition to renewable energy sources is now a one-way street to maintain the high standard of living of modern society and mitigate climate change.

It is well-known that fossil fuels are finite; renewable sources of 'green energy should replace them'. More specifically, RES should cover more than 80% of the world's energy demands. Energy storage is another problem to be addressed, which is of the utmost importance. There is no such problem with fossil fuels, as the energy supplier (electricity grid) provides them with uninterrupted supply and easy storage [3].

Despite the importance of the energy crisis and the imminent dangers, Greece, although having ample solar and wind power potential, still has fossil fuels as the main energy generation source, while RES play a complementary role (Figure 1.1). The dependence rate on conventional energy generation technologies accounts for 68.29% of the total energy generation, while only 31.71% comes from RES, according to the 2018 data.

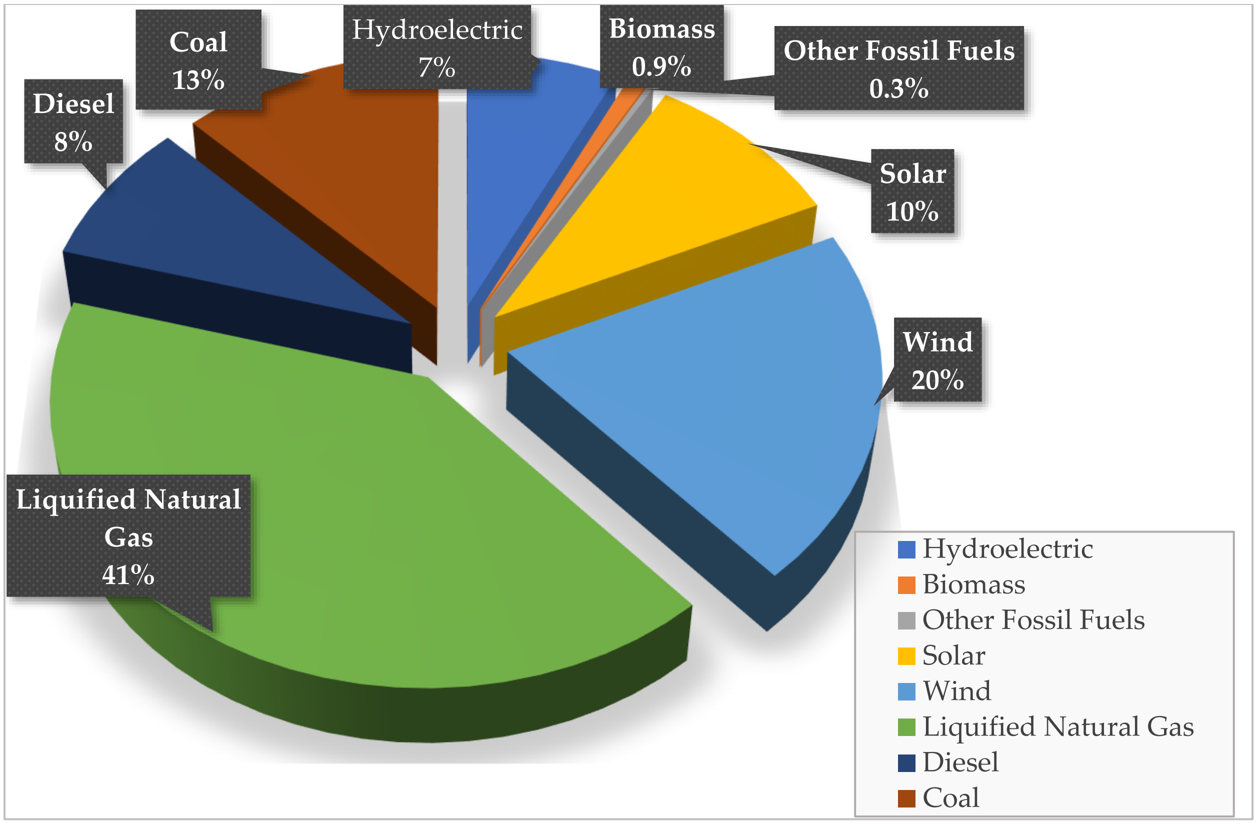


Figure 1.1. Greece's mainland energy mix [4]

1.3. Energy analysis of transportation sector

The transportation sector is one of the most energy-consuming sectors. The transport of EU countries depends on diesel oil by 94%, which is greater than any other sector. The first attempts to reduce GHGs were made with the introduction of biofuels, a policy that will be abandoned after 2020 as the results were not considered encouraging for the future. The first steps towards decarbonization of the transportation sector have been done by introducing green mobility and the mass production of electric vehicles [5].

Maritime transportation is one of the transport sectors which has been of concern to the scientific community due to the complexity and variability of its operations. Cargo transportation is an essential part of international trade, and marine logistics are fundamental to global shipping. Maritime trade channels convey billions of tons of cargo aboard cargo ships.

Maritime shipping is the most efficient and low-cost mode of transportation, but it is also the dirtiest, handling over 90% of global trade and 94 per cent of commerce in poorer countries. Most ships, especially those operating in international seas, continue to use polluting heavy fuel oil.

Ports also have large variations in their energy profile throughout the day and the year due to their complex and unpredictable operations and services [6]. Such services require significant amounts of energy that must be readily available to be used when necessary. Nevertheless, ports are vital for each country's economy, especially for a country like Greece, a highly naval-dependent country. In addition, ports are responsible for importing goods, human transportation to remote areas (islands, continents), and the money flows control.

The scale of freight transport by sea is so large that it was responsible for 80% of world goods transported in 2015. That is why, as of 1 January 2018, the EU, in cooperation with the International Maritime Organization (IMO), has imposed the measurement of GHGs on ships entering ports, with a total load weight of more than 5,000 tons. According to the Kyoto Protocol, the GHGs are projected to be reduced by at least 50% in 2050 in relation to the corresponding 2008 records.

The EU's Energy Taxation Directive does not apply to shipping. The 2015 Paris Agreement also excludes the maritime industry. Despite this, the Paris Agreement includes non-binding objectives for lowering gross annual GHGs by at least 50% by 2050, commencing as soon as practicable, compared to 2008. Furthermore, the new 0.5 percent global SO_2 emission restriction, which took effect on January 1, 2020, would affect around 70,000 ships globally [7].

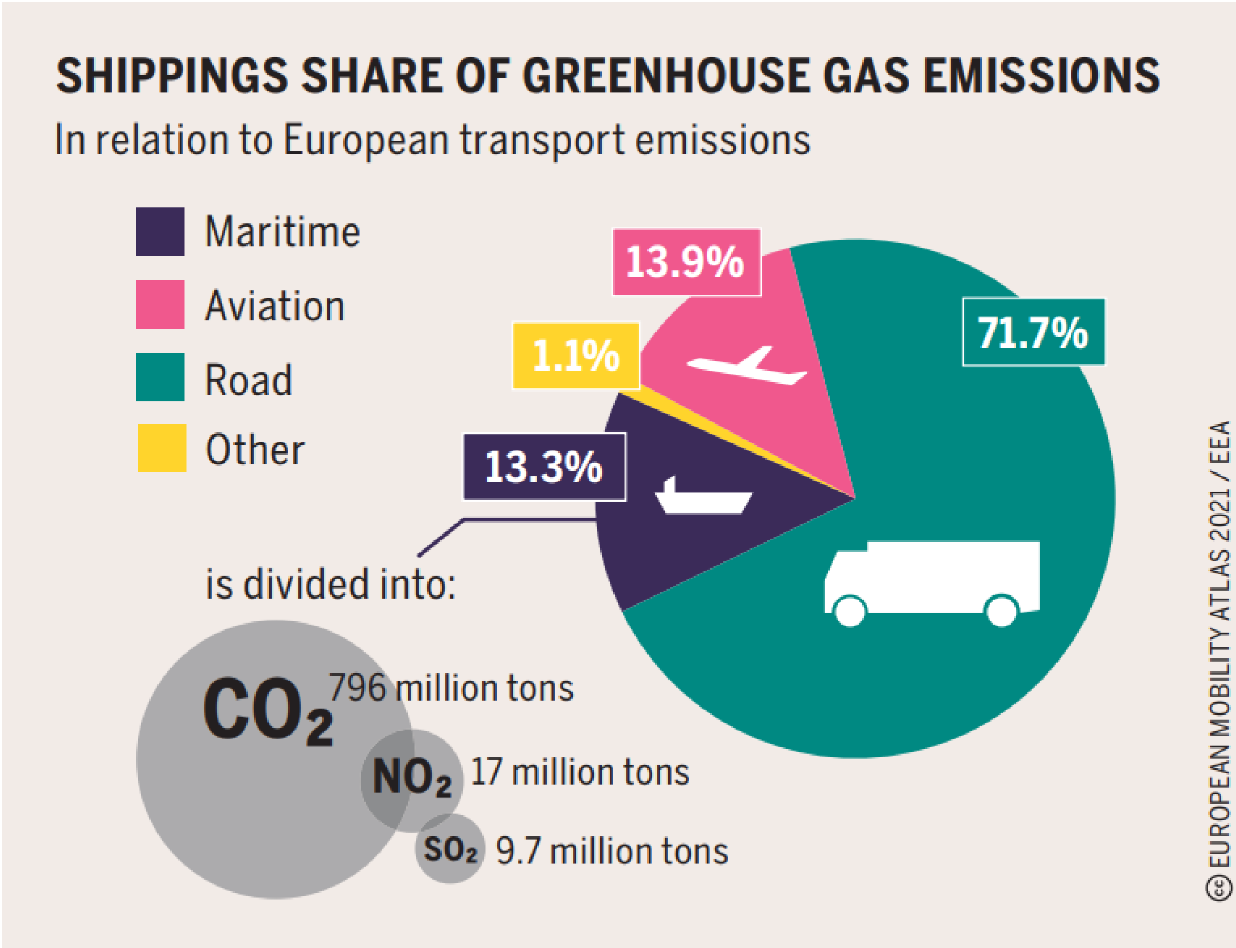


Figure 1.2. Transport-related GHGs in the EU in 2014 [7]

The transportation sector in the EU is divided into four sub-sections, as shown in Figure 1.2. Road transport accounts for 71.7% of EU transport-related GHGs, while aviation is responsible for 13.9%, and finally maritime shipping for 13.3%. This distribution has the effect of contributing equally greatly to air pollution. According to the IMO, it is estimated that due to maritime transport, 939 Mtn CO_2 were released annually from 2007 to 2012, corresponding to 2.8% of the global GHGs. This is expected to be twice as much by 2050. It is worth noting that the movement of ships has explicitly emitted 60% of these GHGs; 20.9 Mtn NOx and 11.3 Mtn SOx per year are estimated to be saved for the same period (from 2012 to 2050).

1.4. The current global state of ports regarding sustainability

Cities, societies, and organizations need to plan their energy transition from fossil fuels to green energy, implementing eco-friendly technologies to the energy supply [8], combined with various flexibility tools [9]. In recent decades, ports both individually and collectively adopt a rigorous and increasingly progressive attitude, hoping to ensure their readiness to become members of a sustainable community soon. Authorities shall adopt relevant directives to upgrade their ports to pave the way towards sustainably achieving their objectives. The efforts' majority focus on innovative future-oriented initiatives, including modernization through the embracing of technological progress and digitization strategies, increased assets' use, increased awareness of environmental security and the transition to green energy. Energy transition, being a critical modification in the current production system, plays a part globally, as it has a central role in the strategy and the orientation of decentralizing the power generation sector and establishing a sustainable power supply [10]. New applications are set through the energy transition, and new long-term goals and paths are defined [11,12].

Most ports frequently experience unforeseen and dangerous situations [13]. These longer-term stresses impact port infrastructures and jeopardise international trade's stability and reliability, as ports are a vital node to the global transportation sector [14,15]. Thus, ports are integrated transport centres and logistic platforms for international trade, and their main commercial activity depends on them. Besides, climate change effects will not be globally standardised [16–18], so that port authorities will require regional climate scenarios to determine the range of potential climate 'futures' for individual ports and their supply chains to consider [19–21]. Their contribution to the phenomenon is high, as their gradually rising production and trade volumes lead to increased energy consumption and more significant air pollution[22–24], which may threaten public health [25,26]. Besides, ship operations have become a significant cause of environmental pollution in port cities, and thus policymakers worldwide attach great importance to managing and tackling this issue [27–29]. Shipping can be traced between 70% and 100% of pollution at seaports in developed countries, while trucks and locomotives account for up to one-fifth, and infrastructure pollution barely reaches 15% [30,31].

Moreover, ship emissions can travel up to 500km of land, and GHGs are well-known to lead to various adverse health impacts, such as asthma and cardiovascular diseases [32,33]. Indicatively, the maritime sector's global emissions account for more than 15% of NOx and SOx emissions and almost 3% of the total CO2 emissions [34]. Therefore, the need to manage consumption trends [35,36] and achieve independence from fossil fuels is more imperative than ever [37]; the role of ports is of vital essence [38].

In response to these issues, European Commission's (EC) plan for efficient, safe, and secure energy sets the priority actions till 2050 to positively mitigate climate change supporting the sustainable yield of products and services [39–41]. In 2018, Renewable Energy Systems (RES) accounted for almost 25% of all energy produced and comprise 18.9% of the European Union's (EU) energy sector. EC endorsed a target of at least 32.5% energy efficiency (EE) and a 32% share of RES in total energy consumption in all sectors by 2030. The EU decided to become the world leader in the implementation and use of RES; the number of installations and investments is projected to rocket up soon [42]. The International Maritime Organization (IMO) set the International Convention on the Control of Emissions from Ships, which took effect from January 2015, and limits ship sulfur content in an Emission Control Area (ECA) to 0.5%; the sulfur content cap is 3.5% above the ECA [43]. Therefore, ports' decision-makers are forced to comply with even stricter environmental regulatory requirements [44–46]. It would take a considerable commitment to achieve these mitigation targets in terms of emerging technology and other steps to adjust the maritime industry towards zero emissions without hampering global trade and economic growth [47]. It is well known that all ports face several challenges, such as air quality, energy consumption, noise, liaison with local communities, climate change, and safety of supply [45].

Concerning the development and sustainability objectives of the United Nations (Sustainable Development Goals - UN SDG), it has been established that achieving long-term global growth is inextricably linked to the principle of sustainability. Therefore, the objective to be implemented is to achieve global sustainability, with UN 2030 Agenda organizing the program entitled 'Transforming Our World', which focuses on 17 sustainable development objectives (SDG) and 169 targets integrated into three key pillars: (a) the economic growth, (b) social development, and (c) the environmental protection.

On 22/03/2018, the World Ports’ Sustainability Program (WPSP) was launched in Antwerp. The project was launched in 2017 by the International Association of Ports and Harbors (IAPH). The UN-SDG is at the heart of the WPSP and aims to strengthen ports worldwide by making a significant contribution to achieving these goals. Furthermore, WPSP aims to empower workers, authorities and other parties operating in the port to collaborate with private and governmental institutions to develop sustainable programs and partnerships that will bring welfare to the ports’ surroundings. The direction that the European Commission (EU) is seeking that beyond systems and policies, port development strategies must be based on sustainability.

EU-funded Docks of the Future (DTF) project is also underway, focusing on the sustainability of future ports, which considers not only economic but also social and environmental aspects. DTF is attempting to define future sustainable ports in Europe and is expected to achieve its objective through a five-stage sustainable plan involving smart port enterprises, environmental protection, work development and local citizens’ welfare, planning for a bright, sustainable future.

1.5. The current state of the two most prominent Greek ports

In attempting to identify Greece's two main ports, taking into account both the operations in them and their environmental footprint, the ports of Piraeus and Thessaloniki are selected.

1.5.1. The current state of the port of Piraeus

Piraeus Port Authority AE (PPA) presented the first decision to take active measures to tackle sources of pollution from ships and industrial activities in the Piraeus region. According to the PPA, the measures operated by China's COSCO company focus on efficient waste management, noise monitoring, water and air quality control, energy efficiency improvement, and energy savings through recent implementations on various technological aspects. In particular, an integrated environmental assessment study has been developed, which includes both the port and future projects' activities and how the environmental aspects that will be activated in the future will operate and characterise.

1.5.2. The current state of the port of Thessaloniki

The port of Thessaloniki is one of the most important ports in Southeast Europe, serving an enlarged hinterland, especially in the Balkan region. Because of its geographical location and excellent road and rail connections, it is the largest transit-trade port in the country and serves the needs of about 15,000,000 people. As part of a broader plan to keep pace with government and social efforts to combat climate change, the company has chosen to support the green prize holders, certifying ships demonstrating high safety & quality standards and excellent environmental performance. As a result, the port of Thessaloniki offers a 15% discount on port fees for green-priced ships.

1.6. Sustainability priorities of ports

The European Sea Ports Organization (ESPO), in its Annual Environmental Report in 2019, presented the top 10 environmental priorities of European ports, including more than 60 different environmental performance criteria, through the participation of 94 ports (Figure 1.3). Over time and taking advantage of data from 1996 to 2019, a change in priorities for the various activities taking place in ports has been observed. In recent years, there has been a commitment to finding solutions to improve air quality, which stems from the increasing GHGs, and the deterioration of air quality, which cause social discomfort and health problems. Also, the ever-increasing energy demand needs to be reduced. The overwhelming increase in the importance of limiting the phenomenon of climate change is noteworthy, as, before 2017, this criterion was not even on the list of the 10 most important criteria and is now in a prominent position. About eight out of ten European ports take climate change into account when developing new infrastructure projects. In addition, 62% of ports strengthen climate resilience through the current infrastructure, and 47% of them have already faced operational challenges due to climate change. Reducing noise pollution, improving relations with local society and managing ship-generated waste remain high priority areas [48].

Figure 1.3. Top 10 environmental priorities of European ports for 2019 [48]

1.7. Main ports activities

The more frequent activities that are carried out in a port area are as follows in Table 1.1:

Table 1.1. Main activities taking place in a port area [3]

Activity	Description
Air conditioning maintenance	The repair and maintenance of refrigeration/heating appliances in enclosed spaces is imperative in order to achieve thermal comfort in the workplace of operators involved in the port
Maintenance of boilers	The purpose of burning fossil fuels from boilers is to heat enclosed spaces and water and to co-generate electricity. The environmental impact of boilers results

	from gaseous emissions generated during the combustion of fossil fuels, from cooling and cleaning waste and from solid waste from ash disposal
Cargo handling equipment	The Commission is aware of the importance of the European Parliament's role in this area and of the importance of the European Parliament. All (conventional) modes are common to the consumption of diesel fuel for operation.
Loading and unloading of goods	The goods shall be loaded and unloaded by the aforementioned means on the vessels, trucks, railway vehicles and cargo warehouses.
Construction activities	Examples include demolition, repair, construction, warehouses, pipelines, docks, public space, roads, railways, the infrastructure required by new tenants, barges, utilities, etc.
Cruise ships berthing	The most frequent cruise ship activities are drinking water & electricity supply, solid waste to be deposited, fuel supply, dry cleaning chemicals, passenger land transportation provision, pharmaceutical services, electrical equipment maintenance and lighting with LED lamps (Light Emitting Diode), fluorescence incandescent or halogen.
Maintenance and cleaning of equipment	The procedures in the port area require equipment, which must be occasionally maintained and cleaned. Examples include cranes, trucks, excavators, refuse collection vehicles, pumps, tugs, tracers, asphalt

	towing devices, fuel tankers, cement tugs, engines, etc.
Power-supply	The supply may involve ships, trucks and other equipment. It is divided into fossil fuel, water (drinking & general use) and electricity supplies.
Removal of solid waste	It relates to solid waste from office spaces and outdoor spaces. Occasionally errors occur in the process of collecting them, resulting in their possible extension along the lines of ownership and the roads and the barrier of sewage.
Storage	The renting of storage facilities in ports is a frequent occurrence, bringing profits to the port authority. In many cases, tenants must have a cooling system or humidity control system for their products.
Maintenance of port ownership	Key related activities include management of hazardous solid waste, maintenance of equipment vehicles, fencing repair/replacement, structural repairs, building of infrastructure at the request of tenants, overheating of ventilation & air conditioning, maintenance of electrical equipment, sanitation, cleaning, pest/pesticide control, removal of snow with salt or sand, quality control for drinking water, emergency response for truck accidents, chemical leaks & fuel, ship maintenance and dredging instrumentation control.

1.8. Energy generation technologies

The most common energy generation technologies can be classified into two main categories, depending on the deployed resources: conventional energy generation technologies and green energy generation technologies. Figure 1.2 demonstrates the main technologies for both the categories:

Table 1.2. Energy generation technologies [3]

Energy generation technologies	
Conventional	**Green**
Charcoal	Solar energy
Lignite	Wind energy
LNG	Hydraulic energy
Petroleum	Biomass
	Biofuels
	Geothermal
	Wave energy
	Tidal energy

The conventional production methods are characterised by the exploitation of fossil fuels, which come from natural sources, such as the anaerobic decomposition of dead buried organisms. Energy production is based on combustion, and the conversion rate to electricity is exceptionally high, providing storage for future use. Green energy production methods exploit renewable energy sources (RES). These resources are inexhaustible, which are constantly being physically replaced and have a common characteristic of environmentally friendly behaviour, as their exploitation does not contribute to the deterioration of the atmosphere or natural resources of the environment.

Energy production is achieved by converting the various forms of soft energy into electricity by induction. The conversion rate is not exceptionally high, and energy storage is challenging with significant losses if it is not used in the short term. Finally, nuclear energy, which is the energy produced by the transformation of the cores of individuals, is also worth mentioning. The installed global renewable energy capacity in 2016 is presented in Figure 1.4.

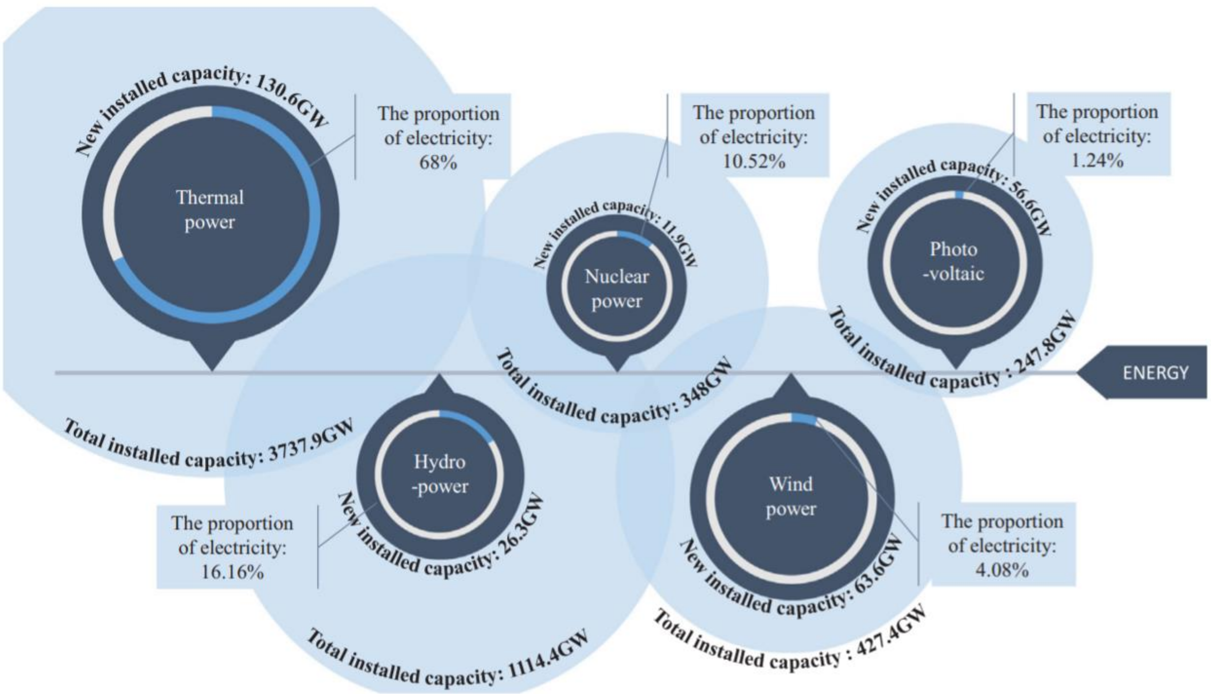


Figure 1.4. Installed global renewable energy capacity in 2016 [3]

1.9. Ports International organizations and environmental assessment tools

Several national organisations have been established to protect maritime shipping. Typical examples are presented in this section.

1.9.1. International Maritime Organization (IMO)

In turn, the IMO has taken steps to reduce GHGs over the next few decades. An emission measurement method was introduced first, the so-called Energy Efficiency Design Index

(EEDI) [16]. This method calculates the GHGs in gCO_2 per nautical mile and is differentiated according to the ship's characteristics.

Thus, there is now an international way of measuring emissions by setting the first uniform global targets. The first target is a 10% reduction, with a further review every five years, including technological progress in the calculations. The EEDI method was developed to cover the most polluting maritime sectors such as tankers, cargo ships, refrigerators or a combination of these. Later this category included LNG ships as fuel, cruise ships and those transporting vehicles. Overall, these categories of vessels account for about 85% of the CO_2 emissions of international transport. The mandatory amendments through the IMO are the following:

- Reduction of GHGs from ships;
- Application of a sulfur emissions limit in 2020;
- Action plan for marine plastic waste;
- Implementation of a convention on the management of polluted waters;
- Adoption of guidance on other environmental issues;
- Technical cooperation and the creation of new measures.

1.9.2. Ship Energy Efficiency Management Plan (SEEMP)

In addition, to further consolidate the above measures, SEEMP was created to improve the economic performance of ships [17], which is a more general and targeted plan. The first action taken was an in-depth summary of climate change, the work required, and the future objectives of the IMO to create technical tools and courses. These tools and training programs were later channelled to shipping companies to reduce the emissions of all types of pollutants (solid, liquid or gaseous).

1.9.3. Marine Environment Protection Committee (MEPC)

The first attempt was handed over to MEPC under MEPC 62 [18] on 1st January 2013 and continues to this day with continuous revisions, reaching MEPC 74 for 2019 [19]. Regarding the practical part, the Energy Efficiency Operational Indicator (EEOI) has been created, a tool that shipping companies can use to improve overall fleet efficiency. Its installation shall enable the measurement of the fuel efficiency and the optimal route selection to reduce GHGs. Furthermore, one of the latest additions to the SEEMP to increase the performance of the commercial fleet is the training and information of staff on environmental issues to understand the importance of their work in them. Combining these two instruments covers a wide range of issues, both in terms of human education and technology, to lay the foundations for future improvements.

1.9.4. Results of SEEMP and EEDI

The countries that decided to follow the IMO regulations account for about 80% of world trade and 75% of CO_2 emissions. The IMO regulations are mandatory for all ships over 400 tons gross tonnage, regardless of the country from which they come; these regulations were set into force on 1 January 2013 and are expected to save 420 $tnCO_2$ per year by 2030. In particular, the percentage reduction by 2030 is foreseen to be between 19-26%. In economic terms, for the same period, the financial savings are estimated at $90-310 b$, respectively.

1.10. Port legislation

1.10.1. International port legislation

The United Nations established the IMO in 1948 to develop and maintain a comprehensive regulatory framework for shipping. Its remit today includes safety, environmental concerns, legal issues, technical cooperation, maritime safety and maritime efficiency. IMO conventions have been ratified by most countries, including Greece. Despite the efforts, there are still environmental aspects that are not fully covered, and there are important conventions that all the Member States has not ratified. Each Member State is responsible for adapting the contracts to its legislative system.

These conventions set standards for many aspects, such as the MARPOL Convention 1973/78 and its annexes on ship-source pollution, which are laid down in the regulations on preventing oil pollution, noxious liquid substances, solid waste and air pollution caused by ships. The London Convention (1972) lays down regulations for preventing marine pollution from the discharge of waste and other water into the sea. Thus, current international legislation constitutes an environmental framework covering the most important environmental aspects for preventing or regulating the potential pollution arising from human activities [20].

1.10.2. Port legislation in Greece

The Greek Port Regulator has the general task of overseeing and ensuring the legality of the relationship between public and private operators in the national port system, in terms of the contractual order and the application of free competition law. This is a basic 'infrastructure' for the observance of legality to protect direct and indirect users of ports, ports themselves, the Greek state, providers, and planned investments. Furthermore, this makes it possible to resolve disputes and reduce conflicts. In accordance with the Articles 112,113 and 114 of Law 4389/2016, the regulatory authority for ports has the following responsibilities:

- Adoption of a regulatory, directly enforceable regulations and decisions, binding directives and opinions;
- Exercise of contractual rights of the Greek State through concessions;
- Methodology and transparency of port changes and access issues;
- Dispute resolution as an arbitration body and emergency measures, where there is a breach of the law, inspections in undertakings, etc.;
- State advisory body on port, legislative and urban issues.

1.11. Thesis innovation

The thesis innovation is presented in this subchapter. After a thorough literature review, the research gaps in the available literature are explored, and the inadequate research areas are explicated to deliver a future agenda for the aspiring researchers and port decision-makers. Thus, this thesis firstly **enriches the current bibliography** and, therefore, provides future researchers or authorities with the capability to draw reliable conclusions regarding possible sustainable measures and technologies into ports.

On the energy forecasting aspect, this thesis enriches the current literature by predicting a port's energy demand profile with relatively high accuracy for 2030 while there are no similar researches on this specific field. Although different energy forecasting models have already been established for other sectors, no similar studies are related to port ones. The innovative aspect is highlighted by using actual hourly 5-year data for the models' training regarding the energy demand of a Mediterranean port, which has not been examined before.

As for introducing an **outdoor-lighting-related smart control system**, this research fills several research gaps and rectifies some of the current open issues in lighting control systems for outdoor spaces. This typology responds fast and accurately to any unpredicted and unexpected alteration of the smart-control parameters, such as the daylight or space's occupancy. Every sub-space is handled individually by the presented SOLCS, considering the different legislative and real-time needs, instead of handling the port area in total. The smart control algorithm's main novelty refers to examining, evaluating, and regulating the lighting conditions of 21 subspaces, according to their unique characteristics, at the same time by ensuring the end-users satisfaction and compliance with the legislative standards. In parallel, unlike prior research works, there is no need for multiple illuminance sensors to make this system efficient, which leads to increased investment and maintenance costs. Only one photodetector and an occupancy sensor are required for the system, making the proposed topology more practical and attractive for investment. Also, all three sustainability pillars are considered and equally satisfied, establishing a smart and environmentally-friendly system. The optimization of the energy efficiency and diminishing the GHGs by concurrently complying with the legislative standards and enhancing the user's comfort is examined for the first time, to the best of the authors' knowledge.

Regarding the **optimal sizing of a port HRES**, a holistic framework and typology concerning the whole process of its optimally, in sustainable terms, sizing is established, presented, and evaluated; the utmost goal is to create a sustainable port infrastructure towards the concept of nZEP. Actual data are utilised for the study's purposes, leading to realistic and trustworthy outcomes. Besides, the suggested typology is highly replicable for other port cases; thousands of ports worldwide have similar characteristics and require energy transition schemes. Each port's specific features are quantified during the input data stage, enabling the method's broad applicability. Also, no similar studies are considering the LCA of the suggested technologies to calculate the infrastructure's environmental impact. Based on the examined literature, this is the first time such a study is conducted, opening the way forward for similar initiatives for the future.

On the alternate energy storage option, the **hydrogen energy storage** is examined, and the implementation of the much-coveted **cold-ironing technique**, for the first time in such a study, is evaluated. Although there are various studies in the available literature investigating hydrogen systems, there are no researches regarding port infrastructures. Also, the port's services' insurance through the autonomous proposed HRES is examined for the first time in such a small infrastructure. A holistic and highly replicable typology is established that can motivate future researchers for similar initiatives. The high adaptability of the proposed typology is enhanced due to the existence of thousands of similar ports worldwide.

Lastly, as for the **smart dispatch micro-grid controller**, two cases are examined for the first time in port cases. The actual port's energy demand data, power rates, and actual Greek market data for the suggested technologies are featured. The optimal cases are acquired by minimising the Levelised Cost of Energy (LCOE) and maximising each examined scenario's environmental benefits. The selected micro-grid controllers ensure the whole port's unhampered operation, which has not been investigated in past studies. Concluding, the main goal of this research is to fill the existing gaps of optimal design, sizing and control of an HRES operation into a seaport.

1.12. Thesis outline and objectives

The thesis structure and objectives are outlined below. This thesis attempts to fill the existing research gaps presented in Section 2: State of the art and enhance the knowledge of port sustainability through the nZEP concept. First, a literature review is answering to the following questions:

- Which are the main categories of ports from the perspective of nZEP? What may be their unique characteristics?
- Which are the available techniques, measures, and technologies that can be implemented into ports, diminish their GHGs, and enhance their environmental footprint? Are they mature enough, or is more expertise needed? Is there any prioritization regarding their implementation to achieve the optimal outcome towards sustainability?
- Which are the opportunities, threats, strengths, and weaknesses of the concept of converting a port to a zero-emission infrastructure? Is it feasible? Are there any examples available in the literature that review the feasibility and the viability of such incentives?
- Lastly, is the cooperation among interested parties strong enough to promote such moves forward? Are they well-informed and concerned about future climate change consequences? What is their perception of sustainability, and which of these measures are included in their business plan?

After this, a statistical analysis is used to identify the key port's energy profile characteristics and aid in establishing its sustainable strategic plan. Also, various forecasting models using statistical and machine learning techniques are examined and compared to predict a port's energy demand in 2030. Finally, the projected energy demand profile is used as an indicator to highlight the urgency and the importance of modernizing a port's operations and converting a port into nZEP.

After finalizing the statistical analysis and the creation of the energy forecasting models, a Smart Outdoor Lighting Control System (SOLCS) is created by the research team to control the port's outdoor lighting efficiently; outdoor lighting into port areas has been proved to be responsible for more than 50% of their energy demand, in many cases. Therefore, this research's main objective is to present, examine and evaluate a novel typology of resizing a Mediterranean port's lighting infrastructures and efficiently controlling them through the suggested SOLCS.

After examining the implementation of a SEMS in the port's outdoor lighting, the prospect of implementing green energy generation and energy storage technologies to cover a port's energy demand is presented and evaluated. A holistic framework and typology concerning the whole process of optimally, in sustainable terms, sizing a port's Hybrid Renewable Energy System (HRES) is established, presented, and evaluated; the utmost goal is to create a sustainable port infrastructure towards the concept of nZEP.

Moreover, the potential of a hydrogen storage system and the implementation of the cold-ironing technique through several assumptions are also examined and evaluated. Specifically, the prospect of embedding a green hydrogen system in a port is examined in terms of autonomy and minimization of GHG emissions by concurrently implementing and examining the impact of the CI technology to the port's energy profile. Lastly, an applied assessment framework is presented to provide insights into the design and the optimal sizing and control of an HRES into seaports, ensuring operational stability and safety. The proposed framework provides a reliable, cost-effective, and sustainable solution for a large Mediterranean port's power supply.

As this study's outline, the prospect of establishing a typology regarding the conversion of a port into nZEP is examined in six steps:

- A literature review is conducted to highlight the importance and the urgency of creating the typology;
- Several statistical methods were used, and various forecasting models were created to indicate the need of modernizing a port's infrastructures and of implementing green energy technologies for its operations;
- A SOLCS was established to efficiently control a port's outdoor lighting operation, reducing the energy demand, and thus the GHGs;
- The prospect of implementing RES and ESS, establishing a Hybrid Renewable Energy Systems (HRES), to cover a port's energy needs is examined through a multi-objective analysis, including techno-economic and environmental and social indexes;
- The potential of introducing a hydrogen storage system instead of conventional ESS is examined by concurrently modelling and examining the impact of the CI technology on a port's energy demand;
- Two control strategies for the port's microgrid controller are examined and evaluated based on a multi-objective optimization process. The port's operational stability and safety are ensured through the implementation of the HRES.

2 State of the Art

The research gaps in the available literature are explored, and the inadequate research areas are explicated to deliver a future agenda for aspiring researchers and port decision-makers. Thus, this study enriches the current bibliography and, therefore, provides future researchers or authorities with the capability to draw reliable conclusions regarding possible sustainable measures and technologies into ports.

2.1. Introductory storyline

Ports are owned, managed, and maintained by various **administration types and stakeholders** differing in size, geological, geographical surroundings, and activities and interests, affecting their final decisions [49–51]. Some central public ports are regulated, including all regulatory and landlord functions; others operate by hybrid public and private custody [50,52]. They are sometimes entirely privatised, with all legislative and operating responsibilities shifted from the public sector, targeting increasing revenues with the minimum investment cost [53]. Thus, the cooperation among all the responsible parties and stakeholders is complex; the conception of a common goal is laborious, and nevertheless, a vague process [54,55]. However, they seem to have typical requirements and pursuits on their operations' development, reliability, and economic viability [56,57]. Such a representative example is that they all have to ensure economic prosperity and industrial activity alongside sustainable development, considering cost minimisation and diminishing risk [58,59]. Several authorities implement a mixture of strategies and measures, including changes in their urban environment, energy consumption, and climate perspectives [60–62], aiming to step forward to a more sustainable future. A list of typical examples comprises the procurement of green towage and dredging, lower berthing times, shorter idling times for the vehicles, and information of the employees and tenants about carpooling, eco-driving, and public transportation, offering advantageous privileges to those who will decide to participate [63].

As ports comprise complex systems that base their operations on internal and external factors, they are inherently connected to social, economic, and environmental-related issues. As a result, they influence their neighbouring cities' performance and the regional socio-economic welfare [64–66]. The ports' geographical location, actual size, number of passengers, ships, ownership, stakeholders, and decision-makers define and apply their distinct management strategies and business plans [67]. According to past research studies, port operations are vital in many circular economy cases among the port and surrounding cities [68–70].

Ports have gradually drawn academic interest due to their complex nature of operations and the different viewpoints that had to be addressed. Indicatively, characteristic examples are the evaluation of the importance of altering their operations towards sustainability [71–73], the environmental impacts of shipping operations [74,75], the sustainability of their logistics [76–78], the assessment of their operations' sustainable potential [79–81], the examination of the possibility of implementing RES for green energy production [82,83], and the efficiency of the installation of SEMS into their infrastructures to enhance their EE [84–86].

The first and most crucial step for any industry planning to reduce its' GHGs [15,87,88], and mitigate climate change [89–91], is to implement **monitoring and real-time reporting systems**. These systems establish a reliable, long-term database, which offers substantial capabilities. Ports will benefit as they do not frequently alter their energy-demanding operations; there are only a few disruptions on energy consumption trends through the years [92,93]. Various authorities have already installed such systems in their industries, including ports in the EU and worldwide [94,95]. There were notable benefits to their EE and their public image [96,97].

EE is gradually gaining attention from ports worldwide, as their authorities realise and appreciate the actual energy savings' potential [98,99]. Luminaires and buildings contribute to ports' energy consumption, and therefore, to the increase of GHGs. Besides, for most ports, the technologies installed for both the heating/cooling operations and the indoor/outdoor lighting are old-fashioned; several ports have started renovating both parts, installing light-emitting diode (LED) lights [100], as well as new Heating, Ventilation, and Air Conditioning (HVAC) systems. Furthermore, the operations can be automated using smart sensors and controls in both technologies, optimising customers' and employees' comfort [101,102].

Ports are mainly attempting to move towards sustainability by employing smart strategies and technologies [103], such as **on-shore power supply** [104,105] or **cold-ironing**, which allows ships at the dock to shut down their fossil-fuel engines [106] depending on electricity for their mandatory operations [60,107,108]; this leads to considerable energy savings [109–111]. Furthermore, it can be either used for other activities, such as port container terminals (PCT), cargo handling, e-vehicles to provide them with power, deriving from cleaner fuels, or RES[112,113]. Another study disclosed that micro-grids could further improve ports' operations towards sustainability by optimising to serve the cold-ironing technique [30,114]; the optimal potential is achieved when the local port grid depends on RES [115]. Compared to other technologies, it is frequently utilised globally, and the effects on the overall EE are outstanding [86,101].

Peak-shaving or load shifting allows the high energy demand dispatch to off-peak hours, relieving the electricity grid and accomplishing substantial GHGs reductions [116,117]. While arriving at ports, **vessels' speed reduction** can be crucial for reducing ship-related emissions and has been proposed a lot in past research works as an easy-to-implement, although effective measure [118,119]. Another helpful technique is the **virtual arrival of ships**, which reduces the vessels' travel speed on their way [120], leading to even 40% less fuel consumption [92,112,121].

An issue affecting sustainability and energy consumption is the stability of the transport phases of goods and the costly re-handling operations [122]. Port authorities have started using other power sources for ports' energy-demanding equipment, primarily electricity, to ensure their services' reliability. **Electrification** of cargo handling equipment and trucks with batteries [123] has been evaluated [124] and proved that the energy and GHG reductions could exceed 60-70% [125,126]. **Hybrid electrified vehicles** are well-known and consume both fossil fuels and electricity; many ports use them for their operations, mainly the cargo ones [127,128].

Automation of the services and operations can enhance the overall efficiency; existing applications on Rubber Tired Gantry (RTG) cranes, PCTs, and other various services had positive consequences to both GHG emissions reduction and other side-effects [115,129,130]. **Mooring systems** can be automated; various ports are already taking advantage of such a move forward [118].

Green port development [46] and sustainable policies reduce ports' environmental footprint and enable green energy supply to their operations [131]. **RES installations** [132,133], such as wind [134,135], solar [136,137], tidal [138], wave [139,140], and geothermal energy [63] are high on demand. Photovoltaic systems (PVs) and geothermal energy harvesters can be utilised for energy production or water heating. In contrast, wind, ocean, and tidal turbines can be exploited exclusively for energy production hitherto. **Energy storage systems (ESS)** can be utilised to reinforce port authorities' attempts towards sustainability [141,142], as long as they can provide reliability and stability to the electricity grid through green energy generation and to reinforce several types of equipment (trucks, RTGs), rocketing up the EE [141,143,144]. Representative examples can be the trucks and the cranes, storing and distributing back more than 60% of a port's actual daily energy needs [145–147].

As a source of cleaner energy**, alternative fuels** could also be used to power port equipment, such as freight handling equipment (PCTs, RTGs, yard cranes), trucks, and boats, as well [19,148]. The most common is the Liquefied Natural Gas (LNG), which could also benefit port operations [149]. Hydrogen can be the optimal prospect of alternate green fuels; it can be used in fuel cells to power engines, tackling climate change. Meanwhile, ports worldwide have initiated using fuel cells for several operations [150,151]. Bioethanol, at low loads, is harmless for the environment, but no research works are available in the literature regarding ports using it. Besides, several ports have exploited biofuels and biomass [152], mainly deriving from the conversion of waste for their operations, mostly freight ones. The utmost advantage of biofuels is that they can be mixed with other fuels; the outcome is a 30% cleaner, on air pollution terms, fuel (i.e., biodiesel) [153].

Future ports wishing to implement the reviewed technologies and measures must be reinforced with **micro or smart grids** that enable the optimal operation through automated tasks in many services. There are ports worldwide that have already employed smart and micro-grids for their operations with significant economic and environmental benefits[32,107]. The synthesis and the optimal combination of the available techniques and technologies to a broader concept, that of nZEP (Figure 2.1), has been proven to decrease the environmental footprint by more than 90%; the green energy production can be over 98% [154,155].

After reviewing all this research work, there are various **research opportunities** for both port authorities and future researchers; several research areas are not well-examined (few research studies), as discussed in the following subsections.

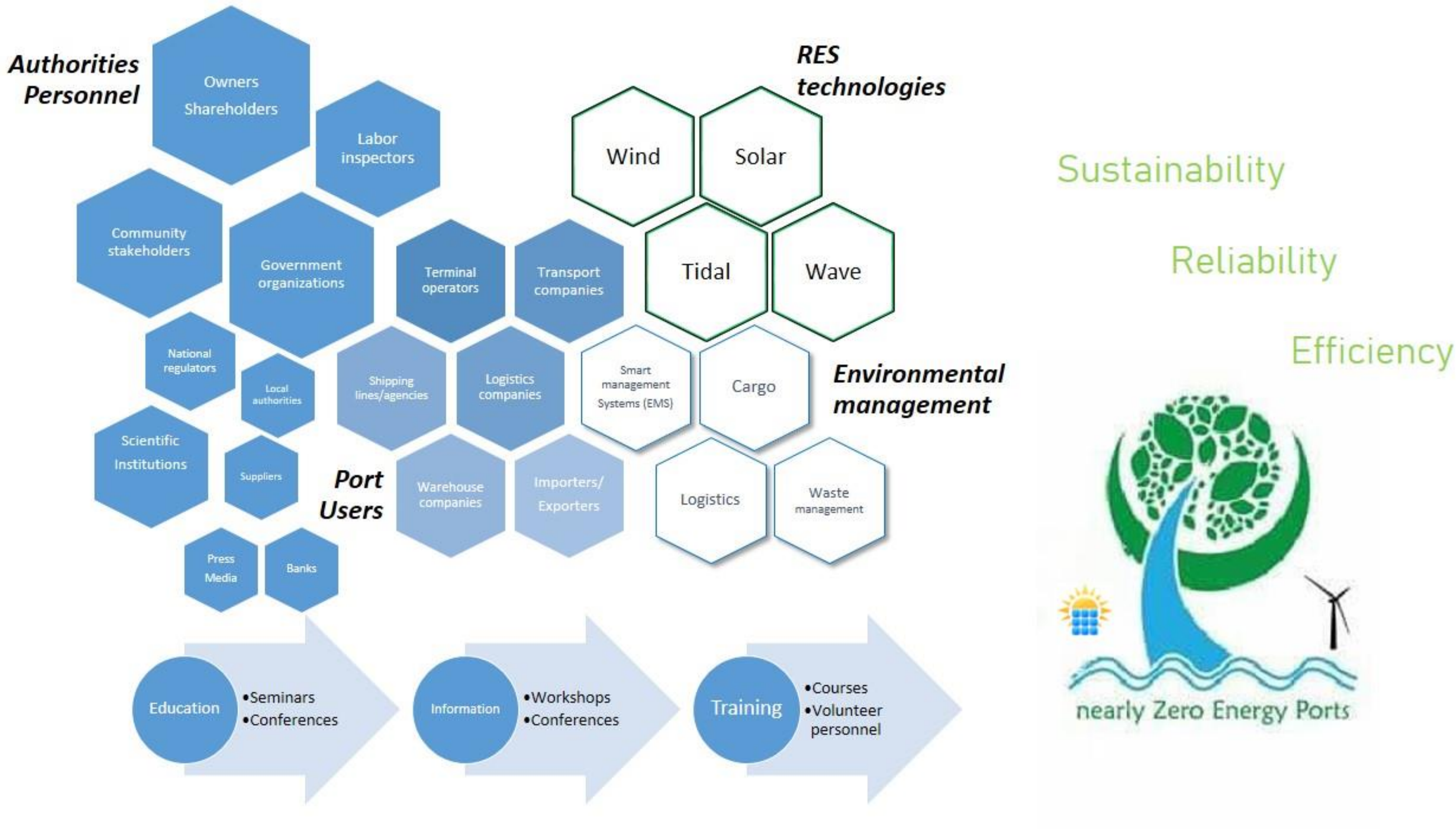


Figure 2.1. Port-related parties, available RES, and "greenable" operations (Source: Author)

2.2. Forecasting models

This subchapter refers to previous research in forecasting energy demand profiles by using machine learning models. Although no relevant research has been found regarding establishing models for ports' energy profiles, various researches have been conducted to create forecasting models for other sectors' energy demand profiles. Typical examples are industries, homes, islands, etc., forecasting energy demand in the short and the long term.

Studies have been performed to determine the forecasting model with the highest accuracy in predicting energy demand, either by classical statistical methods or by machine learning models[156]. Methods such as time series analysis, regression analysis, econometrics, ARIMA, and AI techniques such as fuzzy logic, genetic algorithms, support regression vectors, and artificial neural networks are widely used to predict energy demand [157].

For the models' creation, the installed capacity and the gross domestic product (GDP) (indicators of economic growth) are often used as predictors to the energy demand profile [158]. Also, the per capita income, the LCOE, and the population are used as prediction variables, as they highly impact the energy demand [159] [160]. In addition, meteorological data, mainly the temperature, have been used due to the direct correlation with energy consumption in buildings and industries [161]; other parameters such as the relative humidity, wind speed, etc., are also used, as they also affect energy consumption [162]. *Unfortunately, there are no available research studies regarding forecasting a port's energy profile due to the complexity of acquiring the actual energy demand data of a port and the low research interest to such a sector five years ago*.

The machine learning models that have been extensively used to predict energy demand can estimate the actual values, presenting a mean square error (MSE) well close to zero and a relatively high R^2 index [163]. Machine learning models such as the Random Forest Regression (RF), Linear Regression (LR), Gradient Boosting Regression (GBR) have been used in past studies to estimate energy demand, leading to reliable and solid outcomes [164]. Support Vector Machines (SVM), Artificial Neural Networks (ANN), and k-Nearest Neighbor (KNN) are also quite popular forecasting methods for the prediction of the energy demand in various sectors; their most important asset is the computational speed of the forecasting models [165]. *Although these models have been used for various sectors to predict their energy demand in the future, there are no studies regarding ports' operations.*

Artificial Neural Networks (ANNs) are a widely used forecasting method for energy demand prediction, which have been helpful for network maintenance planning and market research on which producers and resellers are interested [166]. ANNs achieve reliable long-term forecasts, presenting low errors without demanding the use of multi-year historical data [167]. Because the selection of the ANNs' hyperparameters in their structure (number of neurons, hidden levels) is a complex process when creating ANNs, trial and error techniques are usually used to generate the appropriate ANN for the case study [168]. Also, past researches on the type of ANN that performs best in predicting energy demand showed that deep ANNs perform better than conventional ANNs [169]. ANNs such as the long short-term memory network (LSTM), convolutional neural network (CNN), and multi-layer perceptron (MLP) show quite promising results in the field of forecasting electricity demand, requiring a short training time [170]. The recurrent neural network (RNN) can also fill possible data gaps [171]. *Even though ANNs are widely known, there are no researches regarding the prediction of ports' energy demand using such methods.*

Compared to the traditional statistical models, such as the ARIMA, AI-based forecasting methods seem to adapt better to energy demand fluctuations, perfectly fitting the actual data, accurately locating demand peaks, and achieving shallow prediction errors [172]. Various comparative studies of forecasting models for predicting the energy demand indicate that ML models and ANN are superior to the classic statistical methods in accuracy, computational speed, and prediction errors [173]. Furthermore, LSTM performs better according to six indices (MAE, RMSE, MAPE, C, MBE, and UPA) than SVR, ANN, ARIMA, and MLR [174]. Finally, combinations of a CNN and an ANN, benefiting from the advantages of both methods, have been used, resulting in higher predictions' accuracy compared to the other alternative models such as ARIMA, SVM, Linear Regression, Regression Trees and simple ANNs [175].

As society progresses towards a more sustainable way of life, sectors like port industries must comply with the most recent regulations and environmental policies. Forecasting and strategic planning were always part of human development, and further studies in this field will help in the improvement of existing forecasting techniques and tools or create even more accurate ones. *Unfortunately, although several studies have been conducted in energy demand forecasting, no corresponding case study has been found for ports in the available literature.*

As ports are a vital node in the transportation sector, involving various parties such as ships, trucks, logistics companies, local authorities, citizens, etc., port infrastructures inherently impact the regional economies. Also, ports are known to consume significant amounts of energy for their operations and ensure the unhampered amenity of their services. Thus, the need for a long-term sustainable strategic plan in ports is imperative than ever. Finding the energy demand trends in the upcoming years is a crucial step of strategic planning to countermeasure the energy demand of the ports.

A major prerequisite for such a sustainable strategy is acknowledging the future trends in port activities; projections regarding their operation are indispensable to this procedure. Big data analysis and data mining are vital in finding patterns in the energy consumption of such sectors. Implementing dynamic and accurate forecasting tools such as ML models and ANN, alongside the ever-increasing computational power of modern computers, may give the most appropriate solution.

2.3. Current port's sustainable state

2.3.1. Port-related parties

The process of converting ports to a smart, sustainable, and emission-free infrastructure, as an nZEP aims to be, requires **several associated parties.** These parties barely cooperate, act individually, and not as a team [176,177]. On the contrary, they could collaborate and settle towards a common fruitful goal for all the associated parties [178,179]. A well-comprehensive plan has to be applied; at first, inform these parties of the imminent problems and the coveted goals, then indicate the available technologies and measures, and lastly persuade them to collaborate towards a sustainable future [180]. *Unfortunately, the currently limited, relevant published research works do not permit safe conclusions for port authorities' actual cooperation, sustainability perception, and approbation of the available techniques and measures. Specifically, the few available studies are only about large ports, creating many questions regarding the smaller ports' stakeholders' sustainability viewpoints. A possible explanation is the inability to engage private port authorities, as they operate as businesses and are keen on their long-term profits.*

2.3.2. Port cities

There is insufficient cooperation between ports and their nearby cities. Their past strong relationship is weakening, leading to negative consequences for both parties [181,182]. *Due to adequate literature claims and several instances worldwide, it is urgent to renew and empower this partnership; if ports are willing to alter their priorities and adapt to climate change mitigation, implementing effective techniques and measures, this step is necessary.* This partnership will also be beneficial for **port cities**. It would provoke several positive outcomes, such as the electricity grid alleviation and stabilisation, the upgrade of the city's attractiveness, improved living conditions, and human health prioritisation [70].

2.3.3. Academic interest

As the field's **academic interest** is accumulating, the research team attempted a forecast using statistical tools. The acquired literature was classified by publication date on this scope, taking advantage of various statistical methods[183,184]. In this context, a projection could give prominence to the booming research trend on this specific matter. The x-axis represents two years, and the left Y-axis is about the research studies on this specific period, while the right Y-axis corresponds to the summary of the total studies after 2010. According to the projection of the total number of publications in 2030, the broad nZEP concept has been a snowball in recent years. Therefore, the research's booming trend on the topic is recent, as the number of publications has increased up to 5 times in 2020 from 2010 (Figure 2.2).

Ports sustainability is gaining more attention from researchers and authorities globally [63]. As a result, the number of identified research studies during the last five years is almost two times higher than the previous 5-year period. Regarding nZEP, according to the findings of this research work, most tentative research is taking place in Europe, Asia, and America; the biggest ports worldwide are located in these regions, and the need for research and developments is tremendously high [185,186].

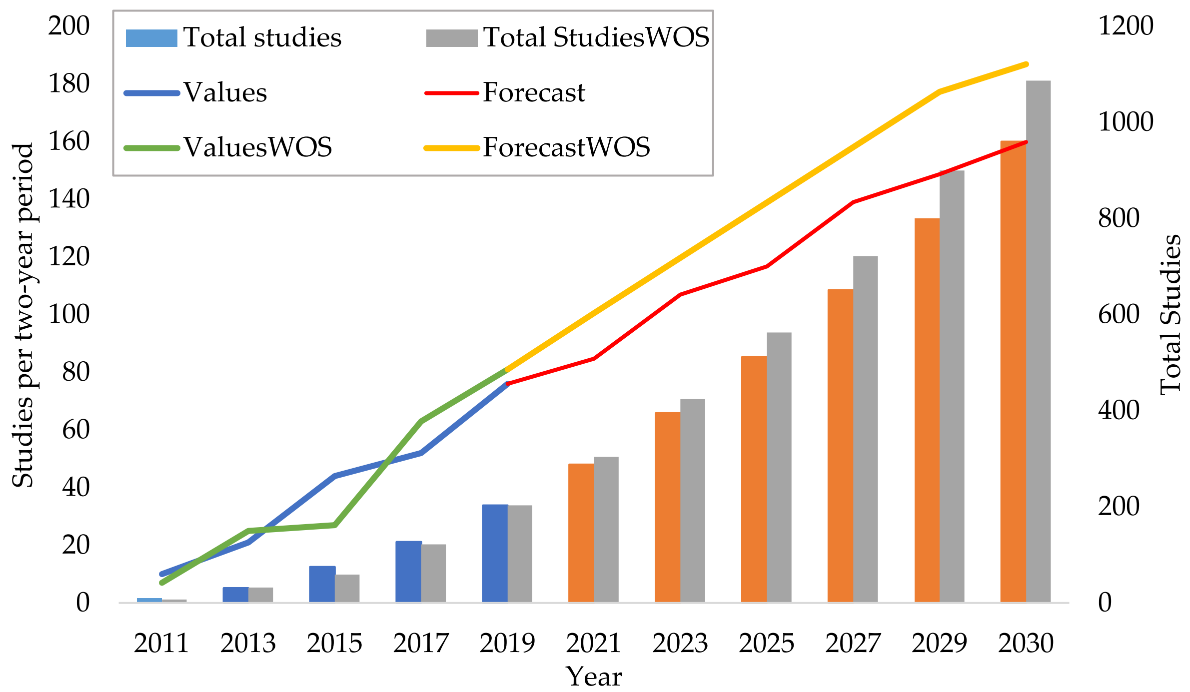


Figure 2.2. The estimated projection trend of studies concerning nZEP in the next decade

*Although the **explored literature** is extensive, covering different topics related to port operations that could directly or indirectly impact energy conservation, there is an inadequacy regarding the number of research works on various examined technologies or techniques. Therefore, the reviewed literature gaps are presented at the end of this section as a future agenda for both researchers and port interested parties.*

2.3.4. Information systems into ports' infrastructures

The acquisition of a detailed, long-term database enables the proper establishment of an energy profile. A reliable database can provide all the required data, in detail, to enable the implementation of the appropriate measures and technologies, aiming at the maximisation of the energy and cost savings, as well as the optimal EE, concurrently improving the regional living conditions [46,187]. The acquired data establish a database of the port's emissions and energy consumption, evaluating its overall energy performance over the years, helping future researchers set a baseline, examining the proper techniques for their aims, and possibly making realistic projections [176]. *Most of the research studies focus on monitoring air pollution in port areas;*

only a few studies incorporate the energy demand's monitoring concerning all the port operations. There is a reasonable explanation why port authorities are mostly rushing air pollution monitoring, as the World Port Climate Initiative has set GHG reduction goals for port authorities [66].

2.3.5. Energy management measures and systems

There are only a few studies on the actual evaluation of the port operations' EE; these utilise surveys, which take advantage of their actual energy demand data monthly or yearly [188]. However, various key performance indicators and conceptual frameworks have been established and implemented into several ports to address the issue [88,189].

2.3.6. Energy efficiency measures on lighting and HVAC systems

Although ports have implemented several EE measures, they remain high-energy-demanding infrastructures. Typical examples are the lighting and heating/cooling systems, especially when the incorporated technologies are old-fashioned or not correctly maintained [190]. First, the old equipment's modernisation is necessary, replacing it with LED lamps and heat pumps. Afterwards, installing appropriate sensors ensures these systems' optimal operation, avoiding energy wastes [27,100]. *Many examples in the literature have incorporated this exact order of actions to enhance the EE of their infrastructures; the energy savings were, evidently, substantial.*

The ever-growing energy demand does not allow the entire fossil fuel abandoning, even though the use of clean energy sources is increasing to tackle the imminent energy crisis. In addition to the expanded and stricter environmental legislation, public consciousness of environment-related matters such as global warming and climate change has increased [191]. Until 2030, the share of Renewable Energy Sources (RES) will be more than 32%; the overall energy efficiency will be increased by 32.5%, and, lastly, the Green House Gases (GHGs) emissions will be reduced by 40% [192,193].

Ports are characterised by high energy demand, complex operations, and many end-users; they can be considered communities, villages, or small towns. The primary concern for port authorities towards sustainability is to reducing the port-related GHGs. Superior expertise and experience are necessary to minimise port operations' impact on natural resources depletion and national markets. Ports on-shore operation-related GHGs result in high social costs; seagoing boats and adjacent means of transport also contribute to port-related GHGs [155,194,195]. Most of the current technologies and techniques are outdated; there is a vast need for replacement; remarkable energy savings and a significant decrease in their environmental footprint are imminent [180]. In this context, ports are forced to conform to even stricter monitoring and social regulations. Thus, authorities have already started replacing the existing high-energy demanding infrastructures and implementing Smart Energy Management Systems (SEMS) to strengthen the overall port operations' efficiency [19,41].

Nearly Zero Energy Port (nZEP) is a promising initiative towards ports sustainability [196].SEMS exploitation is an attractive first step to reduce energy waste and optimise port operations' overall efficiency, not only in energy matters [197–199]. This step should be a prerequisite before the RES sizing and implementation [200–202]. Technological growth in the maritime services industry is closely related to various ICTs aiming at safe sailing and improved operations for all shipping players [203].

In parallel, outdoor lighting is necessary for safety and comfort, improving aesthetics [204,205]. Effective use of road lighting helps protect pedestrians and drivers; meanwhile, there are economic benefits [206]. Satellite imagery shows that the amount of outdoor lighting in Europe increases, with cities showing the most incredible intensity, as 72% of the population in Europe live in urban areas with a significant extension of their activities after sunset [207–209]. According to recent studies, lighting constitutes 15% of the total global energy demand and is responsible for 5% of GHGs [210].

A new philosophy has begun for evolving public outdoor lighting to become more efficient, economical, and environmentally friendly in cooperation with the architectural environment [211–213]. Outdoor lighting provides opportunities for social use of public spaces at night and can improve road safety and crime prevention [214,215]. However, outdoor lighting also consumes significant amounts of energy. Therefore this is not only an economic cost for the local authorities, as it represents 60% of the electricity cost in cities, but it also contributes significantly to the GHGs [216]. On the other hand, street lighting can save more than 50% of energy if LED lamps are installed [217,218]. Also, if SEMS are incorporated, the energy savings can further increase to more than 33%, according to existing studies [219,220]. Nevertheless, in April 2017, an EU regulation replaces low energy-efficient lamps with contemporary ones [221].

More than 90 million installed streetlights globally; the energy consumed due to street lighting is more than 114 TWh yearly, resulting in 69 million tnCO2 and eq [222]. The environmental and financial impact of street lighting is expected to increase due to the current urbanisation trends; the number of streetlights is predicted to increase by more than 300% in the upcoming decade [223]. Various studies have revealed that proper street lighting design amplifies the sense of personal protection and safety. An effective and operational street lighting can diminish crime and traffic-collision cases, encouraging socio-economic activities during night-hours. The obsolete ON/OFF lighting technique is based on astronomical clocks, with an annual calendar incorporating a scheduling system that is less efficient than other initiatives with the same purpose [224,225].

Outdoor lighting into ports holds a considerable energy demand share, sometimes exceeding 70% of a port's total energy needs [226]. Due to the current climate change challenges, several methods have been examined to make lighting more efficient, reducing energy wastes. The innovation of Light Emitting Diode lamps (LED) and the exploitation of RES opened new horizons for outdoor lighting studies, entailing energy and economic prosperity [118,129,227].

Three main steps regarding the reliability and energy-saving potential of outdoor lighting are discussed in the available literature:

- the replacement of the luminaires;
- the reassurance and regulation of the lighting efficiency;
- the luminaires' automatic control according to the streets' conditions [228].

Installing a smart outdoor lighting control system (SOLCS) provokes substantial energy savings and financial profits. However, efficiently illuminating a port area and complying with each space's distinct illuminance regulations is a complicated task.

Control systems taking advantage of daylight have considerable energy savings, especially for indoor applications. Daylight harvesting takes advantage of the ambient light to counterpart artificial lighting from the installed lighting systems to achieve a target illumination level, reducing the electric loads [229–232]. Smart office lighting systems are the future trend, as their energy conservation, cost reduction, improvement of safety, and easy maintenance, make them an essential tool towards sustainability [233]. Based on the occupants' location and daylight distribution, LED lighting systems' control can achieve substantial energy savings [234].

Many schemes that selectively dim lights to increase energy efficiency have been proposed, but little attention has been paid to the resulting street lighting system's utility [235]. Substantial energy savings regarding street lighting are achieved by implementing traffic-aware lighting schemes and exploiting suitable predictive models [236]. Interestingly, utilising algorithms can be highly beneficial to outdoor lighting control; several studies have been conducted regarding tunnel lights, promising significant energy savings [237]. Besides, Artificial Neural Networks are a useful tool to control street lights' operation; the employed training algorithm attains significant energy savings compared to other algorithms [238]. Furthermore, such daylight-adaptive and energy-efficient smart lighting control methods can be used to adjust the luminaire's dimming levels appropriately [58]. Lastly, another interesting approach is to create a complete system of both lighting control systems and RES's implementation to create an IoT system and achieve the best possible outcome [239].

As a contribution to the literature, this research fills several research gaps and rectifies some of the current open issues in lighting control systems for outdoor spaces. This typology responds fast and accurately to any unpredicted and unexpected alteration of the smart-control parameters, such as the daylight or space's occupancy. Every sub-space is handled individually by the presented SOLCS, considering the different legislative and real-time needs, instead of handling the port area in total. The smart control algorithm's main novelty refers to examining, evaluating, and regulating the lighting conditions of 21 subspaces, according to their unique characteristics, at the same time by ensuring the end-users satisfaction and compliance with the legislative standards. In parallel, unlike prior research works, there is no need for multiple illuminance sensors to make this system efficient, which leads to increased investment and maintenance costs. Only one photodetector and an occupancy sensor are required for the system, making the proposed topology more practical and attractive for investment.

Also, a sustainability assessment is conducted regarding the effective use of the port's outdoor lighting infrastructures and the efficient illuminance of all the port's spaces. This work challenges encompassing and reviewing the potential of two smart indoor lighting control strategies into outdoor applications. The credibility and viability of this smart system are examined, quantified, and evaluated through the sustainability assessment, enabling future interested parties to implement it or to conduct further research for their specific case; the high adaptability and replicability of this typology enable such initiatives, making it a generic tool for administrative authorities of every sector worldwide.

Ultimately, all three sustainability pillars are considered and equally satisfied, establishing a smart and environmentally-friendly system. Furthermore, the optimisation of the energy efficiency and diminishing the GHGs by concurrently complying with the legislative standards and enhancing the user's comfort is examined for the first time, to the best of the authors' knowledge.

2.3.7. Peak-shaving

As already mentioned in Section 2, peak-shaving is a challenging technique applied in any industrial infrastructure that facilitates RES and ESS[240]. nZEP plans to incorporate both technologies to achieve the zero-emissions target, which is an ideal case for this technique [241]. A few studies regarding applying and evaluating the technique into port operations exist in the literature; the outcomes are fruitful and provoke significant GHG reductions [109,242]. *Furthermore, the experience and the expertise on this technique are well established in the literature for applications in infrastructures other than ports; it seems reasonable that there will be no complications implementing it into ports.*

2.3.8. Vessels speed reduction

As proved, reducing a ship's speed by 20% can lead to even 40% fuel consumption decreases [112]. Therefore, port authorities can lead the way to reduce GHGs by forcing regulations (i.e., high-speed level) or offering incentives to the ship owners towards this concept (reducing the speed of the ships while they are approaching ports) [243]. It can be an excellent measure for diminishing air pollution into port areas accompanied by the cold-ironing technique. *Several works in the literature are promoting this measure as an ideal solution to GHG reduction policies.*

2.3.9. Virtual Arrival Time

The virtual arrival time manages the vessels' speed, according to the existing and the immediate upcoming situation of the port's berth so that the ship arrives without anchoring [92]. The ships' waiting time, at the berths, is thus reduced; the GHGs and the energy costs are decreased. *This technique is well-established in the literature, and the conclusions are drawn regarding its availability and expertise are reliable and safe.*

2.3.10. Cold-ironing

Cold-ironing or on-shore power supply can essentially diminish GHG emissions and tackle climate change [244]. It is noteworthy that, if this technique is combined with RES energy, the result is a green procedure; the entire amount of energy needed for the ships at berth or other electricity-powered activities is deriving from renewable sources (green energy). The potential GHGs and fossil fuel-related energy decreases are outstanding. Cold-ironing can achieve over 95% energy and GHGs savings. However, on the other side of the coin, the high infrastructure cost and the connectivity complexity are critical bottlenecks for some ports [245]. *Though there is slow uptake in ports worldwide, as only 28 have implemented this measure, the available literature is adequate with studies and simulations. This technology is mature and economically feasible; the outcomes are tangible and clear to encourage or discourage future decision-makers from including it in their business plans.*

2.3.11. Electrification/ Hybridization of equipment

The equipment's electrification or hybridisation is the most efficient technology to enhance the energy-intensive PCTs, their current situation, and their overall performance; significant decreases in energy costs, peak loads, and GHGs are imminent. Electric-powered machines are more energy-efficient than fossil-fuel-based ones. However, their initial capital costs and the more frequent damages are critical barriers to their application. Machines, coupled with batteries, result in standardising performance and service rates, removing confusion about response times, and reducing operational costs and human errors. *There is a lack of evidence in the available literature regarding these technologies due to the limited number of available studies; the existing ones prove the great potential for energy savings and GHG emissions diminishing.*

2.3.12. Automation on port operations and services

By electrifying the existing machinery, the asset of automation is enabled. As a result, the overall port's performance can be enhanced, and the savings can be significant. Automation includes several tasks that may result in less traffic congestion into port areas, reduced container shambles, optimised travel distances, and improved lifting procedures by minimising unnecessary lifts [246]. Another effective automation technique concerns the systems that can reduce the mooring operation time; it can save more than 1.5 h to ships and reduce vessels' turnaround time. The benefits are environmental and economical, making this technique necessary for every port authority that can afford it. The key drawbacks include that the human interferences are decreased, there is a high dependency on electrical equipment, and if the automated tasks are not correctly programmed, they may lead to accidents. *In conclusion, the automation sector is more than 30 years old; both the expertise and the maturity in the field are more than adequate. Various available studies regarding automation in port infrastructures can reinforce those mentioned before and guide stakeholders to judge if the technique is appropriate for their case.*

The reviewed technologies and solutions regarding environmental management are presented in Table 2.1.

Table 2.1. Available environmental management-related techniques/technologies main characteristics

Technology/ Technique	Application Area	Description - Operation	Risks	Advantages
EE measures on lighting and HVAC systems [27,100]	All ports	Replacement of the obsolete equipment and the implementation of smart sensors	- High initial capital	- High energy efficiency - Automated tasks - Fewer energy costs - Better comfort conditions
Peak-Shaving / Load Shifting [109,242]	All ports	Shift of the energy demand from peak to off-peak periods	- High dependency on RES	- Fewer energy costs - Less stressed electricity grid
Vessels speed reduction [112,243]	All ports	Reduce the vessels' speed during berthing	None	- Fewer energy costs - Less GHGs - Less noise
Virtual Arrival Time [92]	All ports	Management of the ship's speed in a way that the anchoring is not needed	None	- Fewer energy costs - Less GHGs - Less noise - Enhanced just-in-time berthing

On-shore power supply, cold-ironing [101,107,247–249]		All ports	Berthed ships plug into the shore electrical network and use energy from the electrical grid instead of the combustion of fossil fuels	- High investment costs - Complex connections	- Capability of achieving a nearly Zero Energy Port - Less GHGs into the port
Electrification of cargo handling equipment [250]	Shore to ship cranes [251]	National & International ports	Replacement of the existing cargo handling equipment with recent fully electric ones	- High initial capital - More frequent damages - Depend on the electricity grid supply	- High EE - Less noise - Automated tasks - Disengagement from fossil fuels
	Rail-mounted gantries [252]				
	Rubber-tyred gantries [141]				
Hybridisation of cargo handling equipment [253]		National & International ports	Replacement of the existing equipment with recent fuel-electric ones or plug-in electric hybrids with batteries	- Very high initial capital - Noisy	- High EE - Independence from the electricity grid

Automation of PCTs[179,246]	International ports	Installation of SEMS to control the PCTs' operations automatically	- More frequent errors - Increased risks of accidents - High investment cost	- Higher EE - Less energy costs - Less traffic congestion - Lower turnaround times
Automated mooring systems [118,254]	All ports	Remote-controlled vacuum pads and hydraulic actuated arms for the mooring	- High initial capital - Increased risk of accidents	- Lower turnaround times - Less GHGs into the port

2.4. Renewable energy systems

RES can significantly reduce GHGs and effectively tackle climate change and its consequences [183]. In addition, generating on-site green power at ports can significantly reduce port-related GHGs, improve the public opinion and social acceptance of ports, and reduce their energy-from-grid demand [255].

2.4.1. Power production from Renewable Energy Sources

Most of the research works regarding RES power generation into ports were about PVs since it is the most cost-effective and mature solution. PV systems are utilised for green energy production [82,133,256,257], or water heating [252,258], and are common in off-grid applications. After simulating several PV systems into ports, they are a useful measure for nearly zero energy and low carbon ports [103,136]. Rooftop PVs (ships' docks, buildings' and PCT' roofs) are the most preferred option, as they can produce significant amounts of energy; they also take advantage of unexploited areas. Besides, various research works describe wind resources' exploitation either into port areas [136,142] or not far away from their territory [259–261]. There seem to be restrictions due to the need for spacious areas for ports keen on installing wind turbines (WTs), either on-shore or offshore, which makes the experience and expertise on the technology relatively low. Although this technology has been more energy-efficient than PVs, and the other available RES, the initial investment cost and the negative social acceptance make it a less preferred solution [133]. For offshore WTs [262,263], special contracts must be signed with the wind farms' developers regarding the energy purchase protocol and the electricity grid. Lastly, it is proven that this technology can improve smart grids' efficiency if combined with ESS since there is almost always energy generation, even if the wind speed is low [180].

The most common ways of harnessing ocean resources [264] are wave and tidal energy. However, they both have some crucial disadvantages, for the time being; even if they can be predicted at some point, there is limited reliability on such machinery, and their cost is still exceptionally high [265–268]. *Moreover, these technologies are* *growing but are still immature and are not preferable by the port authorities; the related literature is insufficient.*

Geothermal energy serves two main direct uses, energy production[63] and heating/cooling, taking advantage of the heat deriving from the earth's layers. According to the literature, the most common use of geothermal energy is heating and cooling buildings [201]; Only near-surface geothermal energy is applied to EU ports. *There is an inadequate number of relevant research studies on this field; no conclusions can be drawn regarding this technology's efficiency and applicability on ports.*

2.4.1. Energy Storage Systems

There is a fair range of solutions available for storage technology that can be divided into mechanical, thermal, electrical, electrochemical, and chemical energy storage [269]. Pumped hydro storage (PHS) is the leading technology, as it is cheaper and more technologically mature than any other available storage method [270,271]. On the contrary, PHS future development is limited because of its specific geographical prerequisites and probable environmental impacts [272]. Various studies have examined and indicated the most appropriate energy storage technology as an auxiliary power source for RES. Today most RES incorporate Photovoltaic Systems (PV) for energy production and batteries for energy storage purposes, depending on the availability of renewable energy resources and the load demand [273]. PV is the most common RES due to the availability of the solar resource [274,275], and the technology's gradually decreasing initial costs alongside its low environmental footprint [133,276].

Up to this point, one of the critical variables compelling the benefit of renewable power sources has been the frailty of batteries to store enough power to provide users' needs during periods that RES cannot. Traditionally, batteries are used to accompany PVs to store the excess energy during the day and solely provide it during the night, when there is no PV production because of the lack of sunlight [277–279]. Although batteries are an efficient storage system, they also have some critical disadvantages, according to past research [280,281]. This type of storage is expensive, large per unit of stored energy, and can solely be used for short-term storage. For instance, a PV will need many batteries to ensure the power supply's stability and operational reliability [282]. Also, the lifetime of batteries is significantly lower than the other energy storage systems; they need to be replaced several times during the lifetime of a 25-years project [180]. However, most systems include an auxiliary generator to provide the remaining energy in extreme load demand periods or during unexpected occurrences; this increases the initial capital and operational costs [283,284].

Also, remote areas, such as small islands, face two major problems, (a) the fuel transportation problem and (b) the lack of an electricity grid and unhampered, reliable power supply [285,286]. Consequently, research studies are to establishing Hybrid Renewable Energy Systems (HRES) incorporating different renewable technologies, such as PVs, Wind Turbines (WT), biomass, hydroelectric [287], or even wave and tidal energy resources [288,289]. PVs and WTs have been examined and evaluated in several past studies, proving that these two technologies are the two key players for HRES [290,291]. Other RES, such as hydroelectric, biomass, and wave/tidal energy, are less known to be used for HRES due to the infrastructures buildup, their operational complexity, their immature technologies, the low expertise on the field, and their high initial capital [292–295]. Therefore, HRES is preferred to comprise PVs, WTs, and batteries used for backup power supply, establishing power-autonomous systems [296–298].

Past research on HRES has indicated that such a sustainable system is feasible and viable and can alleviate cities' electricity grids from peak demands during high daily or seasonal load demands. Especially in the concurrent integration of PVs and WTs alongside a battery storage system, the renewable fraction can exceed 90% for on-grid applications [299–302]. As for off-grid applications, such HRES are capable of supplying all the necessary power at any time of the day, diminishing the chance of unmet loads due to the existence of an auxiliary generator [303–305] or several battery systems [306,307]; though, on the case of integrating an auxiliary diesel generator, the GHGs are not diminished. A past study shows that a 0.161$/kWh Levelised Cost Of

Energy (LCOE) is possible for a green HRES in Bangladesh [308]. Another study, using actual market data, indicated that the LCOE of a hybrid grid-connected system could be less than 0.10€/kWh in Greece [180].

A feasibility study of an island's standalone HRES indicated that the island could be wholly energy-independent; the proposed HRES can be a cost-effective solution with an LCOE equal to 0.595 $/kWh [309]. A standalone microgrid developed with solar photovoltaic (PV)/diesel/battery for a small town of Western Australia made evident that the integration of a PV system with battery storage alongside the existing diesel generators could play an essential role in reducing the cost of energy production, fuel consumption, and generators' operating time [310]. Also, the incorporation of an HRES combined with a diesel generator could reduce the energy load and emissions in Saudi Arabia. It was found that a system with a 35% RES contribution was most effective compared to the single diesel-powered system [311]. Another study, incorporating an HRES including biomass, showed that the LCOE of such a system in India is 0.2899$/kWh, and the GHGs emissions can be significantly reduced [312].

As already mentioned, PVs and WTs depend on weather conditions, which lead to uncertain, intermittent power supply [313,314]. Although batteries provide a solution for short-term energy storage, there is still difficulty storing energy for long-term periods [315]. It is expected that the introduction of hydrogen systems will help to overcome the storage difficulties and will open the way towards a more sustainable future [316–318]. Few research on the usage of hydrogen-based storage systems for large-scale hybrid green energy input scenarios has been reported in the literature; however, several examples have been reported to date to use hydrogen storage in smaller-scale HRES, i.e., households, small islands. Most recent studies focused on reducing the cost of installing a hydrogen system to be more competitive than batteries.

A combination of battery and hydrogen fuel-cell for a 100% HRES was suggested in another study. This study evaluated different combinations of energy storage systems and concluded that combined hydrogen-battery HRES is an innovative approach for

100% renewable energy systems. The excess energy is eliminated from the energy storage use, and the discounted payback was equal to 6 years; the investment is viable, feasible, and fruitful for future investors [319]. Furthermore, a fuel cell-hydrogen system was proven to eliminate the green power supply fluctuation but not economically viable due to the components' high initial costs [320].

Based on their economic issues, a comparison between PV/Wind/Battery and PV/Wind/Battery/Hydrogen systems was made, based on their economic issues, for a sizeable long-term scale energy storage solution in Australia. After the hydrogen system's penetration into the HRES, the LCOE reduced from 2.54 $/kWh to 0.626 $/kWh. The research team also evaluated reducing the baseload supply of gas and increasing renewable energy penetration with limited generation capacity. The excess hydrogen was utilised in this alternative case, which improved the system's overall economic feasibility. In this situation, the LCOE was further decreased to 0.494 $/kWh [321]. Based on the pilot hybrid project's techno-economic issues, a study on the Amazon region indicated that electricity cost with hydrogen storage system was 1.351 $/kWh [322]. Comparing a PV/Battery, PV/Battery/Diesel and PV/Battery/Fuel cell system for a remote base station, found that even in the best-case scenario (2.5$/lt), the cost of electricity with a diesel generator system was 15% cheaper than the cost of the fuel cell system [323].

Another research indicates that a battery storage system is superior to a hydrogen storage system for domestic usage in Sweden. When a sensitivity analysis was applied to this case, the results revealed that a possible 25% cost reduction of the electrolyser's price would lead the hydrogen storage system to have a similar self-sufficient ratio with the battery storage system [324]. A feasibility analysis was conducted regarding some PV-wind turbine systems and battery and hydrogen storage for a small village in Tioman Island in Malaysia. The study showed that the HRES had an LCOE of 1.104 $/kWh. However, due to reliability issues, a fuel cell was introduced in the solar-wind-battery system in terms of power supply, ensuring the unhampered power supply; the LCOE was reasonably increased to 1.108 $/kWh [312].

Another study on a small island in East Malaysia has shown similar outcomes, but for a lower LCOE, the LCOE value of the proposed HRES without the hydrogen storage was 0.323$/kWh, which slightly increased to 0.355$/kWh after implementing the hydrogen storage components [325,326].

This research attempts to "fill" the research gaps mentioned above. First, the sustainability of small ports is examined, as there are inadequate past studies on this specific topic. Although there are various studies in the available literature investigating hydrogen systems, there are no researches regarding port infrastructures. Also, the port's services' insurance through the autonomous proposed HRES is examined for the first time in such a small infrastructure. Second, a holistic and highly replicable typology is established that can motivate future researchers for similar initiatives. Third, the high adaptability of the proposed typology is enhanced due to the existence of thousands of similar ports worldwide.

An nZEP aims to achieve almost 100% renewable energy penetration, which is why numerous port authorities attempt to install ESS alongside all the above. ESS vary from different types of batteries to flywheels and hydrogen-fuel cell systems. They can be used embedded into trucks or on other electric or hybrid machines, or even discretely to save the RES excess energy and reclaim dissipated energy [141,180,327]. In addition, these systems can provide stability and reliability for the port operations, ease the port city's electricity grid, and deliver an essential means of ensuring the ports' unhampered functionality. Regardless of their multiple advantages, the most critical disadvantage is that they have high initial investment costs, and their lifetime is relatively low, making them an expensive solution. *Unfortunately, the relevant literature in port infrastructures is distinctively scarce for Hybrid Renewable Energy Systems. On the contrary, there is a significant variance of studies for PCTs and freight handling equipment; these technologies are primarily well-tested and mature.*

The reviewed technologies and solutions regarding RES that can be implemented into port areas are presented in Table 2.2.

Table 2.2. Main characteristics of the proposed renewable energy systems

Technology/ Technique		**Application Area**	**Description - Operation**	**Risks**	**Advantages**
Solar power generation	Installation of Photovoltaic (PV) systems [82,256,257]	All ports	Installation of PVs on rooftops or unallocated fields to exploit solar power and generate energy or heating	- Less energy-efficient than the other RES	- Low initial investment costs - High EE - Mature technology - High expertise in the technology
	Solar water heating [252,258]				
Wind power generation Installation of WT into wind parks	Onshore [136,142]	All ports	Exploitation of wind energy sources to unallocated fields	- High initial investment costs - Low social acceptance - Landmark degradation	- High EE - Efficient use of unallocated space
	Offshore [259–261] [262,263]	International Ports	Wind power generation into marine locations away from the shore	- Spacious ports - High initial investment costs - May harm ecosystems' stability	- High EE - Efficient use of unallocated marine space - High social acceptance
	Floating [328,329]				

Ocean power generation [330]	Wave energy converters [265,266] Tidal energy converters [267,268]	All ports	Ocean power generation into marine locations near or away from the shore	- High initial investment cost - Spacious ports - Immature technologies - May harm ecosystems' stability - Low reliability	- High EE - Multiple applications - High social acceptance - Non-existent landmark degradation
Geothermal	Power generation [63] Heating and cooling	All ports	Geothermal power exploitation for energy or heating/cooling purposes	- High initial investment cost - High geothermal potential required - Low expertise in the technology	- High EE - High social acceptance - Multiple applications
Energy storage systems	Power storage, electrification of equipment	All ports	Exploitation of electricity for both energy storage for smart techniques (i.e., peak-shaving) and the electrification of trucks	- High initial investment - Low lifetime of the technology	- High electricity reliability and stability - Electrification of equipment - Incorporation of automated tasks

2.5. Alternative, renewable fuels and waste conversion

2.5.1. LNG

LNG is widely used in many appliances worldwide. Specifically, it can be used both as fuel for both powering ships [290] or other inland operations in ports. LNG's main disadvantage is that it needs spacious infrastructures to facilitate its storage and bunkering points [331,332]. On the other hand, GHG emissions from LNG use are, by far, less than those of petroleum-based fuels. Specifically, the SO_2 emissions are reduced significantly, and CO_2, NOx emissions are reduced by almost 25% [333,334].

2.5.2. Renewable fuels

There are no available studies on using biomethanol as a fuel for ships, and no techno-economic analyses are available, hitherto. Only a few methanol-fuelled vessels are currently operating; the GHG reductions, compared to conventional vessels, are proved to be substantial. However, there are several drawbacks to using biomethanol, i.e., the higher cost than other fuels, the higher GHG emissions during its production, and the lack of experience, as it has not yet been tested for marine impulsion [335–337].

Biomass can be turned either into biogas, or liquid biofuels, which are viable opportunities for ports; the waste biomass produced by their operations can be efficiently utilised instead of fossil fuels, leading to environmental and economic benefits; biofuels can be used to power trucks, for instance [338]. However, biomass and biofuels require specific techniques and equipment during their base exploitation operations. In addition, proper measures to avoid safety hazards are compulsory. A combination of the complexity and the high cost of the machines, alongside the risk of misusing these products, discourages decision-makers from choosing them as an alternative to fossil fuels and researchers from studying them in their simulations. *Thus, there are no enough research works to draw reliable conclusions concerning these technologies; the possible complications in port infrastructures are still unknown* [339–341].

Hitherto, any possible conclusions regarding this type of fuel can only be generalised by international literature.

Hydrogen fuel cells are utilised mainly for storage and to power several types of machinery [150]. They can also be used to power ships [342], but this is not common; only a few vessels of this type currently operate [343]. Various ports have implemented hydrogen for their PCTs, cranes, and other freight handling operations [151]. There are several bottlenecks regarding the use of hydrogen, in general, such as the cost, its dependence on fossil fuels for the separation of oxygen, the storage complications, the trickiness to move it around, and lastly, its high risk as gas. *There is a scarcity of studies about hydrogen as storage in ports, and the available ones, regarding ship powering are not adequate for safe conclusions.*

2.5.3. Waste conversion

Lastly, a vast amount of waste needs to be handled daily; an optimal solution is to produce thermal energy or biofuels. However, there is a need for a considerable initial investment that many ports' authorities cannot afford. *Moreover, the literature's availability is far from satisfactory, as there are only a handful of studies on waste management towards sustainability into ports.*

The characteristics of the reviewed alternative, renewable fuels, and waste conversion are presented in Table 2.3.

Table 2.3. Main characteristics of the proposed alternative fuels

Technology/ Technique		**Application Area**	**Description - Operation**	**Risks**	**Advantages**
Alternate green fuels	Biomass [152,344]	All ports	Exploitation of biomass and biofuels instead of fossil fuels for energy production and heating purposes	- High initial investment cost for the machinery - Low expertise in the technology	- Low-cost fuels - Multiple applications - No landmark degradation
	Biomass [152,344] and Biofuels [345]				
Alternative use of oily waste [29]		International ports	Production of thermal energy using oily waste	- High capital cost and initial investment	- Circular economy - Less energy costs for heating/cooling

2.5.4. Smart – Micro Grids

Smart and microgrids are the missing links for all the available measures and technologies; they offer the capability to control and automate a whole industry [346]. For example, the energy produced by one or more RES can be distributed to the electricity grid by a microgrid, which aims at the optimal cooperation of these two separate systems [347]. Microgrids comprised of solar, wind, and other RES systems offer an opportunity for ports to efficiently meet their electrical energy requirements through green energy and EE [348–350]. The imminent energy and environmental crisis worsen the climate change problem [351].

Ports are energy-intensive consumers, accounting for 3% of global GHG emissions [352]. RES could play a major role in the problem's solution, but the stochastic nature of RES is a crucial bottleneck [353]; an ESS is needed to normalise the fluctuating, unpredictable and unreliable green-power supply [354]. An HRES combined with a smart micro-grid controller could be a viable and feasible optimal sustainable solution [355]. In HRES development, the system's optimal sizing and control are two essential issues to be handled [356]. Several studies have attempted to achieve the optimal outcome regarding the sizing of an HRES incorporating either custom-made algorithms or employing HOMER [357]. This model meets the predefined load specifications with various technologies and resource choices by simulating the whole-year HRES operation [358]. *There is a limited number of sufficient studies on smart or microgrids in port infrastructures, but the expertise and the cost-effectiveness of this technology make its application obligatory for future SEMS.*

3 Methodology

In this chapter, a comprehensive approach to the research's methodology part is presented.

At first, a detailed literature review is conducted to enhance the knowledge of port sustainability and set the base knowledge regarding the available technologies and techniques. Based on a thorough Literature Review of 236 publications between 2010 and 2020, more than ten technologies and 15 EE measures were identified. Various ports worldwide have attempted to install RES, SEMS, and other climate change mitigation measures. The research gap regarding the nZEP concept is highlighted and helps the readers acknowledge this research work's importance.

The case studies' selection is the next step; several criteria were used to pick the optimal ones, covering a wide variety of cases, enabling the extraction of solid and reliable results for all the port categories, establishing a universal and highly replicable typology. The acquisition and examination of the port's actual energy data come next; this procedure was completed through the collaboration with ports' personnel and the implementation of smart metering systems from the electricity provider (HEDNO). Then, the statistical analysis (big-data) is executed using mathematical tools to determine the port's actual energy needs and their allocation for the ports' services. Lastly, several ML models/tools were used to foresee the ports' energy profile for 2030, indicating the need to amplify the current ports' state in energy terms.

After analysing the energy data of the four case studies, the outdoor lighting infrastructures are proved to be the most energy-demanding operation for all the cases; the total renovation of the outdoor lighting infrastructures is the first accomplished task by replacing and relocating the old-fashioned luminaires with new LED ones. A SOLCS was established for the optimal control of the lighting output of the new luminaires according to the sun's illuminance and each port's space occupancy, implementing a non-invasive SEMS into the port activities.

After examining implementing a SEMS, several HRES for each port case are conceptualised, simulated, discussed, compared, and evaluated to pick the optimal among them. The HRES consists of PV arrays, WTs, and ESS. Next, feasible and credible solutions are placed into a candidate pool. Finally, the optimal one is picked for each sustainability criteria, as set by the research team.

The cold-ironing technology is integrated and examined to eliminate berthing ships' emissions harmonised with the most recent EU legislation. Concurrently, the outlook of integrating a hydrogen storage system is evaluated in terms of autonomy and minimisation of the port's GHG emissions; the outcomes are compared to the other examined ESS of the previous step.

The last step is an applied assessment framework to provide insights into the design and the optimal sizing and control of an HRES into seaports, ensuring operational stability and safety. The proposed framework provides a reliable, cost-effective, and sustainable solution for a large Mediterranean port's power supply. It is also highly replicable regardless of the port's size.

The port's total renovation towards a sustainable infrastructure is handled in seven steps:

(a) The past literature's exploration, indicating the proper, available techniques and technologies;

(b) The examination of the ports' actual energy data, establishing the real hourly energy profile through a detailed statistical analysis;

(c) The use of machine learning (ML) techniques to project the future ports' energy consumption;

(d) The renovation and smartification of the ports' outdoor lighting by examining the efficiency of a newly-established SOLCS;

(e) The optimal sizing of the ports' HRES, examining various available RES and ESS technologies;

(f) The implementation of the cold-ironing technique and the use of a hydrogen storage system;

(g) The optimal configuration of the ports' micro-grid energy dispatch system (control) by comparing the available techniques (Figure 3.1).

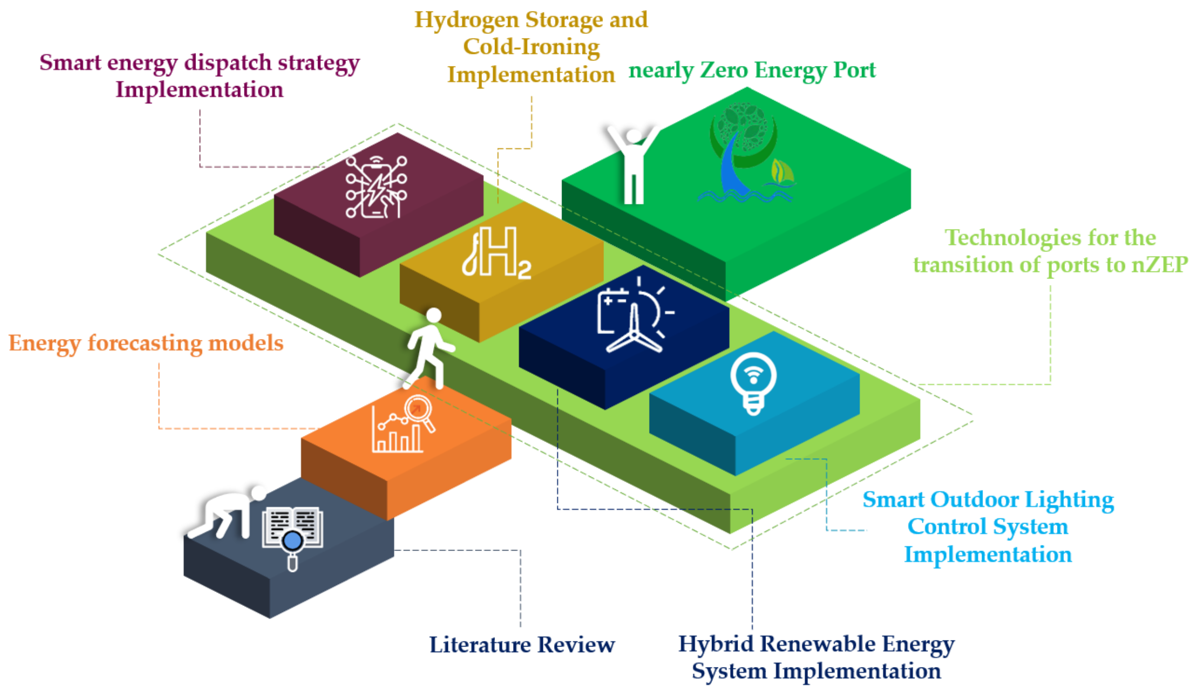


Figure 3.1. Thesis methodological steps

3.1 Review paper methodology

3.1.1. Main steps of the study

A systematic literature review [359,360] has been carried out to avoid potential bias. The research team established a robust database by restricting the literature to academic, peer-reviewed articles, conference proceedings, book chapters, and technical reports published after 2010. All these were included to ensure that there are good viewpoints on the topics of interest; the number of peer-reviewed publications was inadequate in some cases. Meanwhile, usual studies, projects, and regional reports were excluded. Specific titles and keywords were investigated in broad databases, such as ScienceDirect, Web of Science (WOS), Institute of Electrical and Electronics Engineers (IEEE), Explore, Google Scholar, and CiteCeerx. Indicatively, "energy ports", "green ports", "ports sustainability", "port's sustainable development", "sustainable port infrastructures", "ports' air quality", "greenhouse gases into ports", and "climate change and ports" were among the used keywords. The two inclusion and exclusion criteria ensured the selected literature's relevance, decreasing the initial number of results according to the keywords. After the acquisition of all the available literature, several filtering stages followed. During the initial stage, almost 3,000 results appeared; the duplicates, the outdated research works (before 2010), and other irrelevant studies were excluded (n_1=2,158). Right after, the inclusion (high relevance with the nZEP concept, studies that answer the research questions) and exclusion criteria (irrelevance with the research aims, similar studies with minor differences, conference proceedings, and reports) were applied, and almost half of the literature was excluded (n_2=421). As a third stage, an abstract and conclusions scan took place; the research team kept only the high relevant articles (n_3=249). The fourth stage included two sub-stages; at first, the full papers were studied, and after that, the papers that were irrelevant to sustainability, air pollution, SEMS, or RES application into ports were excepted (n_4=201). The snowball sampling technique was applied as the last stage, and the final number of papers was n_5=236. Supplement references, mainly for the availability of the different technologies, were included. Several studies from the broad field of sustainable development were selected to provide a comprehensible and complete literature review concerning all the available techniques applied in ports. The critical stages of the research methodology can be found in Figure 3.3.

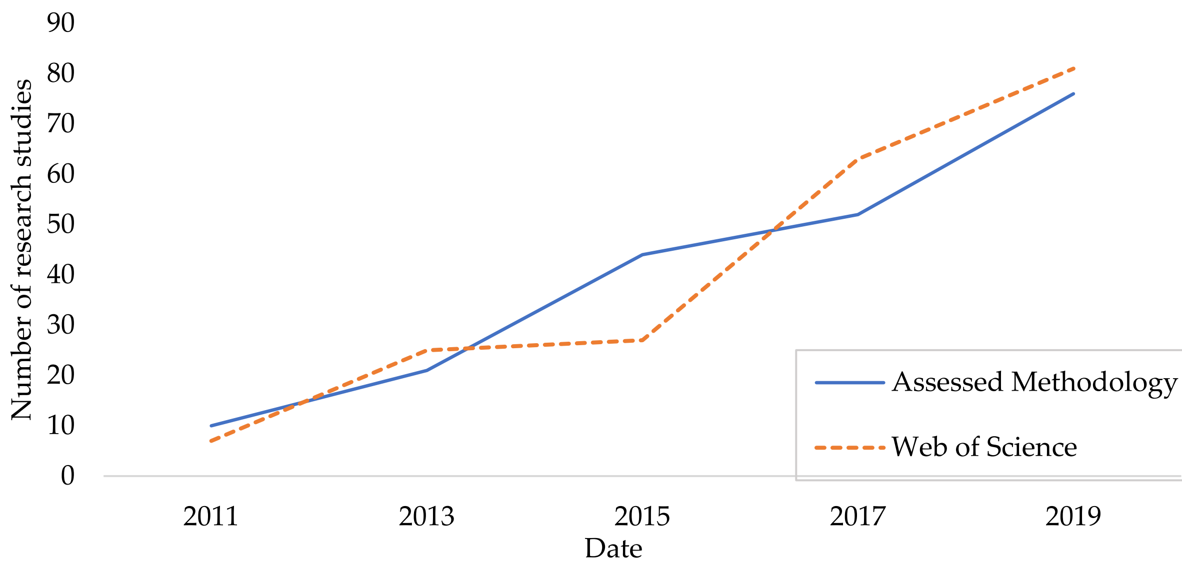


Figure 3.2. The estimated trend regarding sustainability research into ports during the last ten years

During the last decade, there was a booming trend in this topic, proving that sustainability issues are becoming one of the top port authorities' priorities; the trendlines can justify this (Figure 3.2). The WoS trendline is being utilised to check the methodology's effectiveness, refining all the available literature, thus keeping only the high-relevant studies. Even after this, the trend remains almost the same; the actual number of studies during 2018-2019 has a 10-15% deviation.

Besides, a strengths-weaknesses-opportunities-threats analysis (SWOT) has been conducted to evaluate the acquired knowledge regarding the reviewed technologies and techniques; the analysis highlights the prospects and the credibility of the proposed concept (see Section 4).

3.1.2. Typologies of ports

Ports were grouped into three specific categories, labelled with particular characteristics, such as the vessels' type and volume that the port serves, the surrounding region of the port (city), the port's operations and services, the annual number of passengers who visit the port and lastly, the annual number of ships that berth and depart from the port (Table 3.1, Figure 3.4).

Table 3.1. Port categories according to the proposed typology [155]

Local ports	National ports	International ports
Cover an island's needs	Cover a country's needs	Cover a country's international needs
Small-sized	Medium-sized	Large-sized
Do not support cruise ships, and they do not have logistics	Serve some cruise ships; supporting small logistics	Serve cruise ships; supporting logistics

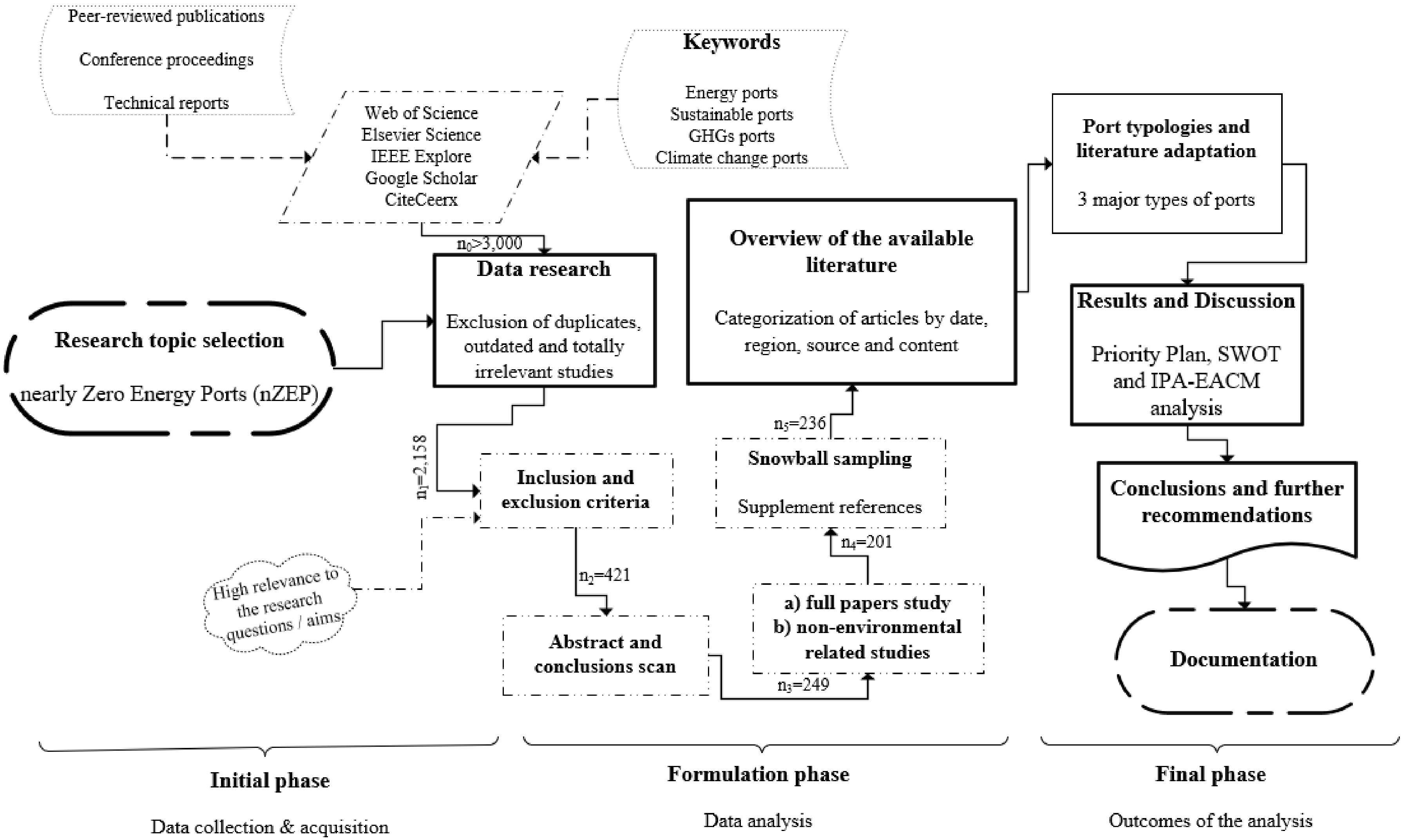


Figure 3.3. Critical stages of the proposed methodology

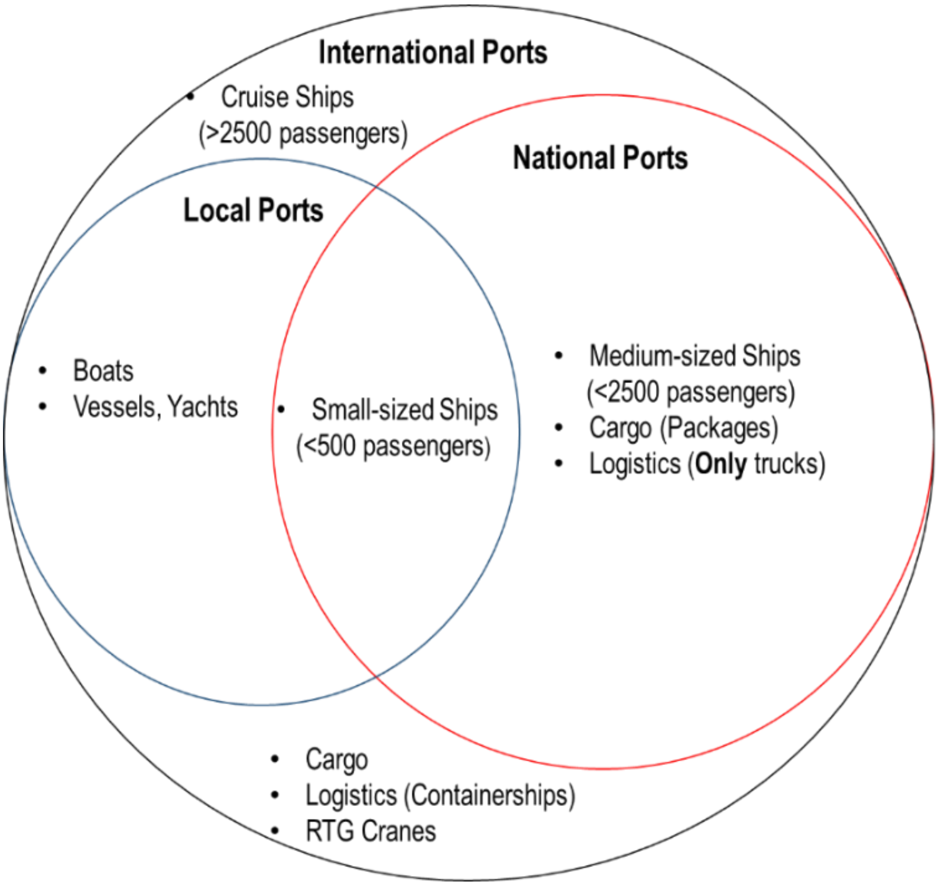


Figure 3.4. Allocation of operations per port category

Local ports: They can serve a small island's needs. Usually, they are occupied by itinerary ships. They do not serve cruise ships as they have limited space and capacity. Lastly, they are not characterised by complex logistic processes, as there is limited space for the load/unload processes that passenger ships can handle, despite their seasonal operation.

National ports: They can serve a country's transportation-related needs (hinterland) and are slightly larger than local ports. They occupy all ship types, but only a few cruise ships are served yearly (once or twice monthly). They have small logistics infrastructures and satisfy the basic needs of the served region.

International ports: They can serve the international needs of a country and are the biggest ones. They offer services to every type of ship due to their adequate space and proper infrastructures. They frequently serve cruise ships. Besides, they facilitate large logistics infrastructures, having the highest greenification potential among all the categories.

3.2 Statistical analysis methodology and future projections using Classic statistical models, Artificial Neural Networks, and Machine Learning techniques

The motivation of this subchapter is to create a future model of the port's power consumption for the year 2030, to examine and highlight the need of converting a port into nZEP, being a prerequisite for a long-term sustainable development plan.

3.2.1 Data acquisition

For the establishment and the formulation of the future energy profile, the actual energy consumption data of the port of Souda were obtained through the cooperation of the Souda's port personnel and the smart metering hardware of the electricity provider [33]. The meteorological data were obtained through the collaboration of the National Observatory of Athens' personnel; smart meters are installed near the port of Souda [34]. After this, several projection models were used, compared, and evaluated to accomplish the study's goal.

3.2.2 Data classification

The area's meteorological data from 2015-2019, obtained from the National Observatory of Athens and 2030, were used to create the forecast models. In addition, data on the electricity consumption of the port of Souda for the years 2015-2019 were provided by Souda's port personnel.

The data are divided into three main categories, which were utilised according to the capacity of each examined model:

- Hourly,
- Daily,
- Monthly.

The used meteorological data for the forecasting models are the following:

- Temperature: Measurable in degrees Celsius (°C)
- Humidity: Measured as a percentage (%)

- Dewpoint: The point of temperature at which water vapours, when cooled, creates the dew effect, measurable in degrees Celsius (°C).
- Atmospheric Pressure: Measurable in hectopascal (hPa)
- Precipitation: Measurable in mm
- Wind Speed: Measurable in km/h
- Solar Radiation: Measurable in W/m^2
- Time Step (Timestep): Integer serial numbers to capture the ascending trend.
- Hour/Day/Month: Integer numbers

The forecast variable is the energy demand measurable in kWh.

The data are divided into these three categories as the monthly data enable comparing the machine learning models with the neural networks and the classical time series statistical models, apart only from the linear regression model. The actual energy forecasting methodology is presented in Figure 3.5.

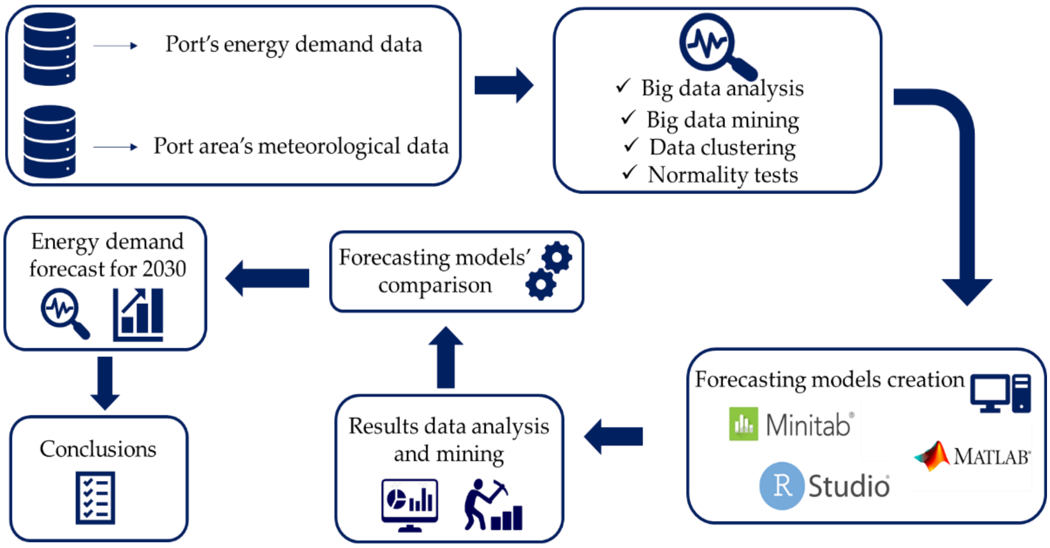


Figure 3.5. Energy forecasting models' methodology

However, the ANN and ML models perform better when there is a larger database; daily data are used, increasing computational requirements. Finally, the hourly data are used for an even more precise forecast.

The linear regression models, the time series splitting, and the ARIMA models are developed in the MINITAB software, which provides a user-friendly and easy-to-understand interface. On the other hand, the machine learning models and the ANN ones are developed in MATLAB's software (Regression Learner App and Neural Net Fitting App).

3.2.3 Pearson correlation

The Pearson product-moment correlation coefficient (r, R, or Pearson's r) measures the strength and direction of the linear relationship between two quantitative variables (e.g., actual consumption and monthly bill charged). Several assumptions needed to be satisfied (namely, level of measurement, related pairs, absence of outliers, normality of the dependent variable, linearity, and homoscedasticity).

3.2.4 Simple Linear Regression

Linear regression is a widely used statistical approach to model the relationship between a dependent variable Y and one or more independent variables X, and the equation that describes it is:

$$Y = Ax + b \ (1)$$

b is the slope of the line and represents the coefficient of coefficient. The model's reliability is shown by the deviation or residual of the observed Y value from the predicted Y value of the model after the regression. The squares of the deviations add up and give the total deviation of the model called the sum of the squares of the remaining RSS (Residuals Sum of Squares). The lower the RSS value, the more reliable the model is considered, while the opposite is true as long as the RSS is relatively large. For more than one variable X that affects the value of Y, the model is called Multiple Linear Regression, and the equation is:

$$Y = a + b_1 \times X_1 + b_2 \times X_2 + \cdots + b_n \times X_n \ (2)$$

3.2.5 Timeseries Models

3.2.5.1 Decomposition method

The time series analysis with this method is based on the breakdown of the observations into four synthetic elements, the trend, the seasonality, the circularity, and the randomness. The purpose of splitting time series is to isolate the above four synthetic elements to determine how they influence how time-series observations are created. First, seasonality is measured by seasonality indices, which detect observations due to this phenomenon, which will help dispel this element and create more reliable short-term and long-term forecasts. Second, the trend reveals the long-term fluctuations of the time series values (up or down) due to demographic, technological, economic, and other factors. Third, circularity is observed in periods longer than seasonality (e.g., five years or ten years about quarterly or annual seasonality) and appears mainly in economic issues, such as an economic crisis. Finally, the randomness is related to random phenomena that may affect the time series and are not easily calculated [60]. In the context of this dissertation, circularity and irregularity are not taken into account as the data are reported for four to five years.

In the decomposition method, there are two types of models, the additive and the multiplier. In the additive, the actual values are displayed as the sum of the components and are as follows:

$$Y_t = Trend + Seasonal + Error \ (3)$$

In the multiplier method, the actual values are presented as a product of the components and are of the form:

$$Y_t = Trend \ x \ Seasonal \ x \ Error \ (4)$$

3.2.5.2 Autoregressive integrated moving average (ARIMA)

The ARIMA model, also known as the Box-Jenkins method, consists of three parts, the autoregression part (AR), where there is a combination of previous values, the moving average part (MA), where it uses previous prediction errors in an almost-regression model and the integration part (I), which refers to the inverse differentiation process for the production of the forecast.

An autoregressive model of order p or AR (p) in its general form is:

$$Y_t = \varphi_1 \times Y_{t-1} + \varphi_2 \times Y_{t-2} + \cdots + \varphi_p \times Y_{t-p} + \varepsilon_t \ (5)$$

where φ_1, φ_2, .., φ_ϱ are the parameters to be estimated of the model and ε_t is known as white noise. The order p refers to the length of the lag and the term self-regression because the above relation is a regression model with interpretive variables Yt's values with a time lag.

A model of a moving average q class or MA (q) in its general form is:

$$Y_t = \mu + \varepsilon_t + \theta_1 \times \varepsilon_{t-1} + \theta_2 \times \varepsilon_{t-2} + \cdots + \theta_q \times \varepsilon_{t-q} \ (6)$$

where the order q refers to the length of the lag of the variable ε_t, which we assume to be white noise. The term moving average refers to the fact that Y_t appears as a weighted sum of the values of ε_t.

An ARMA model (p, q) is a combination of p self-oscillating terms and q moving medium terms, is called a mixed self-reciprocating-moving medium model order (p, q), and has the form:

$$\Phi(B)Y_t = \Theta(B) \times \varepsilon_t \ (7)$$

where $\Phi(B) = 1 - \varphi_1 \times B - \cdots - \varphi_p \times B^p$, and $\Theta(B) = 1 - \theta_1 \times B - \theta_2 \times B^2 - \cdots - \theta_q \times B^q$

A non-seasonal ARIMA model is also called the ARIMA (p, d, q) model, where p is the number of the self-oscillating terms, d is the number of non-seasonal differences required for stagnation, and q is the number of delayed forecast errors in the forecast equation.

Non-seasonal ARIMA is used when the time series is not stationary (e.g., chronological series of economic, energy, or physical content). With the first (or second, generally d class) differences, it becomes stationary. An ARIMA model (p, d, q) has the form:

$$\Phi(B) \times (1 - B)^d \times Y_t = \Theta(B) \times \varepsilon_t \ (8)$$

In addition, in time series that show seasonality s, the SARIMA model (p, d, q) (P, D, Q)$_s$ is used, where P, D, Q are the corresponding quantities of p, d, q according to seasonality s. A SARIMA (p, d, q) (P, D, Q) s model has the form:

$$\varphi(B) \times \Phi(B^s) \times w_t = \theta(B) \times \Theta(B^s) \times \varepsilon_t \ (9)$$

where $\varphi(B) = 1 - \varphi_1 \times B - \cdots - \varphi_p \times B^p$, $\Phi(B^s) = 1 - \Phi_1 \times B^s - \cdots - \varphi_P \times B^{Ps}$, $\theta(B) = 1 - \theta_1 \times B - \cdots - \theta_q \times B^q$, $\Theta(B^s) = 1 - \Theta_1 \times B^s - \cdots - \Theta_Q \times B^{Qs}$, and $w_t = \nabla^d \nabla_s^D Y_t$.

3.2.6 Machine Learning Models

3.2.6.1 Decision trees

Decision trees predict the value of the target variables as accurately as possible according to the input data [61]. Each tree consists of nodes, and each node is linked to one of the input variables. Nodes are extended to sheets that represent the value resulting from the variable. Decision trees always start from the top (root) and end in a leaf (Figure 3.6) [62].

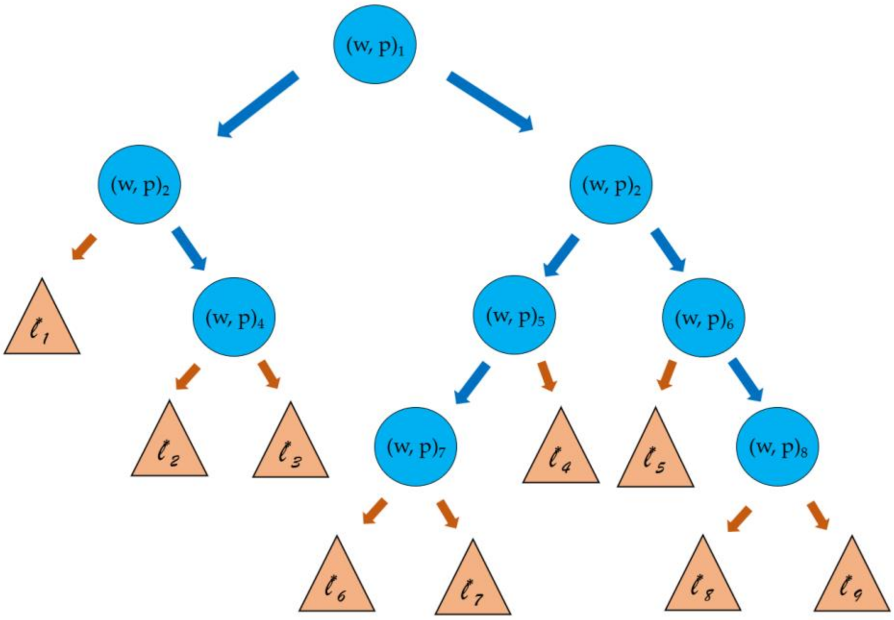


Figure 3.6. An illustration of a multivariate decision tree model (Source: Authors)

3.2.6.2 Support Vector Machines

Support vector machines were first proposed by Vladimir Vapnik in 1992 and belong to kernel methods. Kernel methods use a function that groups the input data, whose behavior is then graphically represented. These methods can operate in an infinite space of unlimited dimensions without calculating the data coordinates in that space, but by calculating the inner product, space produced through the relationships of the data between them [63]. MATLAB implements the linear regression SVM (e-SVM), which is sensitive to e, also known as L1 loss. In e-SVM regression, the set of training data includes prediction variables and observed response values. The goal is to find a function f (x) that deviates from Yn with a value not greater than ε for each training point X, and at the same time be as flat as possible.

A set of training data x_i and variable objectives y_i the goal is to minimise the vector of the hyperparameter w:

$$w = MIN\frac{1}{2}\|w\|^2 , \qquad restricted\ by : |y_i - w_i \times x_i| \le \varepsilon \ (10)$$

3.2.6.3 Gaussian Process Regression – GPR

Gaussian Process Regression is non-parametric; that is, a functional form does not constrain it, so instead of calculating the probability distribution of parameters of a particular function, it calculates the probability distribution of all proper functions that match the data. A GPR model explains the response by introducing latent variables f (x_i), i = 1,2,… n, Gaussian Process (GP), and explicit base functions, h. The covariance of the latent variables reflects the smoothness of the response, and the base functions display the inputs x in a p-dimensional feature space. GP is a set of random variables, where each finite number of them has a standard Gaussian distribution. Based on Bayes' theorem [65], a Gaussian reverse distribution in objective functions are determined, the mean value is used for forecasting.

The Bayesian approach to a linear function y = wx + ε works by defining the previous distribution p (w), in the parameter w and migrating the probabilities based on the observed data, according to the Bayes rule:

$$p(w|y, X) = \frac{p(y|X, w) \times p(w)}{p(y|X)} \ (11)$$

The updated distribution p (w | y, X), called the reverse distribution, incorporates information from the previous distribution and the data set.

GPR learns a target function using the kernel trick internally, uses the kernel to determine the covariance of a previous distribution versus the target functions, and uses the observed training data to determine a probability function. GPR selects core hyperparameters based on the slope of the marginal probability function and learns a genetic, probabilistic model of the target function, providing substantial confidence intervals and back-samples along with predictions [66].

A GPR model is represented as follows:

$$h(x)^T \times \beta + f(x) \ (12)$$

where f (x) ~ GP (0, k (x, x')) from a zero mean GP with covariance function k (x, x'), h (x) is a set of base functions that mutate the original attribute vector $x \in R^d$ in a new attribute vector h (x) $\in R^p$, β is a px1 coefficient base function vector.

An example of a y response can be modelled as:

$$P(y_i | f(x_i), x_i \sim N(y_i | h(x_i)^T \beta + f(x_i), \sigma^2) \ \ (13)$$

where σ^2 is the error variation.

3.2.6.4 Ensemble Methods

Ensemble Methods are combinations of algorithms that cover each individual's weaknesses to optimise the results. Each algorithm that uses meta-learning models splits the data set, at random, into different training/training sets. Then by voting, giving either the same or different weight to each method, based on the evaluation indicators, selects the value with the most votes in case of regression. Occasionally they show an increased computational load.

The bagging algorithm described a classical meta-learning algorithm methodology, which uses a combination of the same methods. In Bagging Trees, multiple decision trees are used in which the respective set of training that will be used as input is randomly selected. The training sets are subsets of the original training set. New combinations are created in each repetition of learning, removing the unsuitable ones each time. Also, another methodology is boosting, which uses voting. He assigns weights to the vote based on the confidence levels of each model and then combines models from the same algorithm. Finally, it performs an iterative process in which it uses any knowledge gained from the previous model to improve the next one that will be developed [68].

3.2.7 Artificial Neural Networks (ANN)

Artificial neural networks consist of simple elements that operate in parallel, and the connections between the elements largely determine the operation of the network. For example, an ANN can be trained to perform a specific function by adjusting the values of the connections (weights) between the elements so that a specific input leads to the specific target output. Regarding how the elements are connected, ANNs are divided into two main categories:

- Feed forward,
- Feed backwards.

In the front feed ANN, the elements are organised at different levels, and the elements of one level feed the elements of the next level, which continues until the last level.

In back-end networks, also known as Recurrent ANNs, single-level components are allowed to power units of the same or previous level. If the feedback concerns nodes of the same level, the networks are called auto-associated memories; otherwise, they are called hetero-associated memories.

Although feed-in ANNs are quite useful, front-feed ANNs are most often used. Also, in multi-level ANN, the most common way of learning is with error back-propagation, which belongs to supervised learning, and the learning algorithm is called Backpropagation ANN. During the training of Backpropagation ANN, for each input given to the network, the outputs are calculated by applying the transition functions to each hidden or external level unit. In each external level unit, the differences between hidden levels are taken into account to configure the connection weights between the units to reduce the output error.

The actual error E_k of an output unit k of an example p is calculated as:

$$E_k = \left(a_{kp} - o_{kp}\right) \ (14)$$

It is then multiplied by the derivative of the activation function in the unit k(u_k), according to the generalised delta rule, to calculate the custom neuron error:

$$\delta_k = \left(a_{kp} - o_{kp}\right) \times g'(u_k) \ (15)$$

The corresponding error in a hidden level i unit is calculated from the adjusted errors in the next level k units to which the unit is associated with w_{ik} weights:

$$\delta_i = g'(u_i) \times \sum_{1}^{k} w_{ik} \times \delta_k \ (16)$$

After calculating for each unit i the error δ_i, the alteration in input weights in all neurons is calculated as follows:

$$\Delta w_{ji} = -d \times \delta_i \times a_j \quad (17)$$

The change in weight from neuron i to the next j depends on the error of neuron i, the output of neuron j, and the learning rate d. Numerous such cycles are repeated during the training process; the algorithm stops when the error has reached below the desired limit. Alternatively, completing a certain number of training cycles can be considered a termination condition for a certain period.

3.2.8 Comparison indexes

For each model, training is done on the data from 2015 to 2019. Then, in each model, the accuracy of the electricity price that each model predicts for the same period is tested, and it is checked whether they deviate from the actual values. Finally, the models are used to forecast the port's electricity for 2030.

As for indicators for comparing the models for predictability, according to the actual data, the following are selected:

3.2.8.1 Mean Squared Error – MSE

The average square error (MSE) of an estimator measures the average of the errors, i.e., the mean square difference between the estimated values of the actual value. It is a measure of the quality of an appraiser and always takes non-negative values, with those approaching zero being the best. For a prediction vector n created by a sample of n data points in all variables and Y is the vector of the observed values of the predicted variable, with Yˆbeing the predicted values, the MSE is calculated as:

$$MSE = \frac{1}{n} \times \sum_{i=1}^{n} (Y_i - \hat{Y}_i)^2 \quad (18)$$

3.2.8.2 Root Mean Squared Error – RMSE

RMSE is essentially the root of MSE (Equation 19), and the reason it is used is that it acquires the same units of measurement as the quantity estimated.

$$RMSE = \sqrt{MSE} \quad (19)$$

3.3 Case studies selection

Four ports of different characteristics are picked for the needs of this thesis according to their daily operations and services, their energy demand and their geographical location (Figure 3.7).

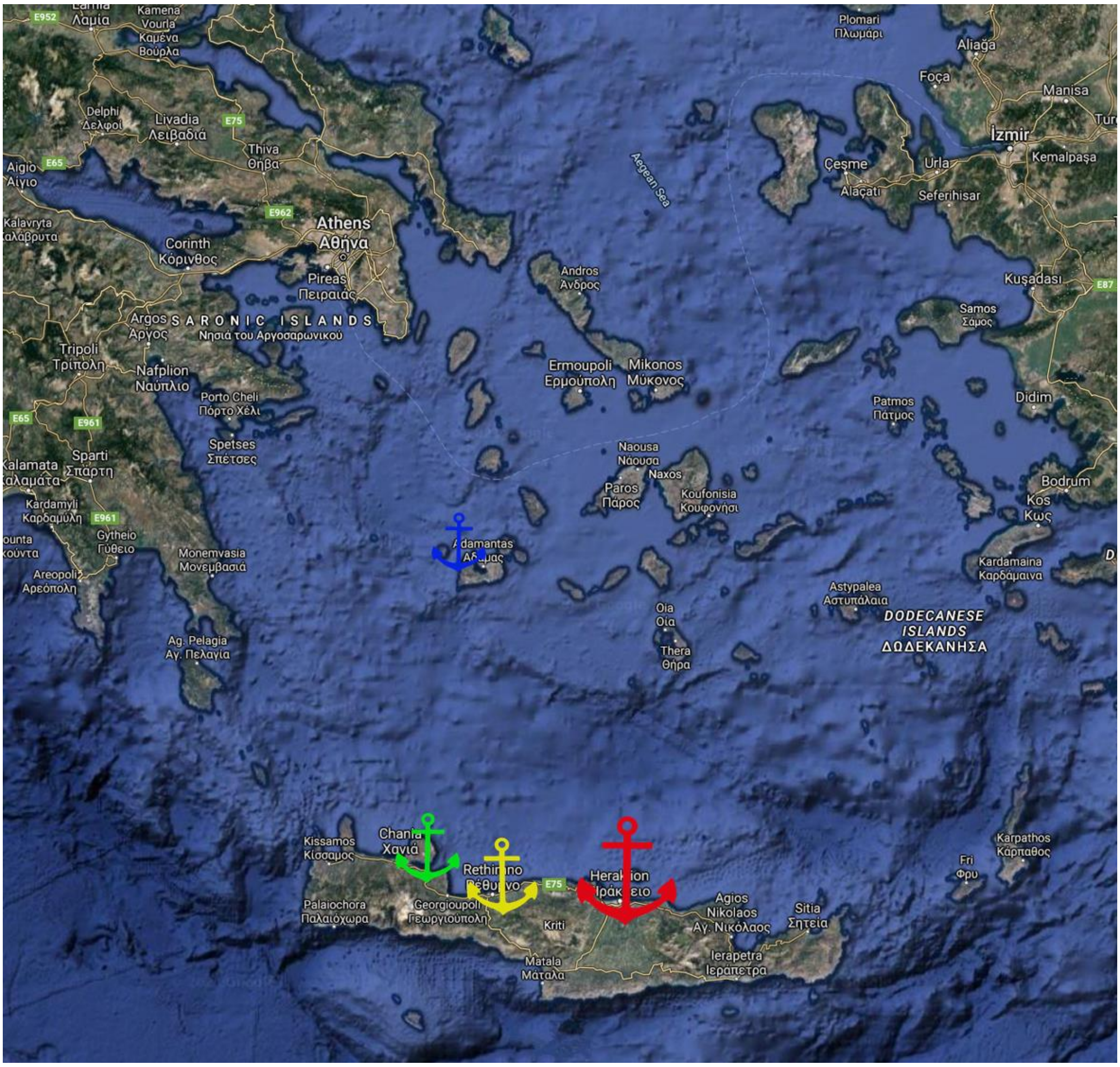


Figure 3.7. Map of all the used ports as testbeds

The selected ports are all located in the Mediterranean Sea and are characterised by great seasonal fluctuation on their operations due to the high impact of tourism. The three out of four ports are in the island of Crete, while the fourth is located in Adamas, Milos Island. Table X demonstrates the technologies that are implemented, simulated, discussed and evaluated into each port according to their unique characteristics.

Table 3.2. Implemented technologies per case study

Case Study/Port	Technology			
	SOLCS	**HRES**	**CI & H_2**	**SDS**
Heraklion		X[1]		X
Souda (Chania)		X[2]		
Rethymno	X			
Adamas (Milos)			X	

[1]Carbon Footprint is calculated using the annual energy purchases

[2]Carbon Footprint is calculated using the LCA of each incorporated technology

Two medium sized ports (according to Figure 3.4 and Table 3.1) are picked. The port of Rethymno (yellow anchor on Figure 3.7) is selected due to its geographical location and its complex outdoor lighting infrastructures. The SOLCS system is simulated and evaluated into the Rethymno's port outdoor lighting infrastructures. Also, the availability of 5-year actual data for the port's energy demand and the strong cooperation with the port's personnel enabled the establishment of the custom SOLCS. The port of Chania (green anchor on Figure 3.7) is selected for the HRES implementation and the CF calculation based on the LCA of each technology due to the availability of adequate space for the systems' installation and the high-RES potential of the Crete Island; the high similarity to the majority of ports worldwide played a crucial role to the selection, due to the high replicability of the proposed typology.

A small port (according to Figure 3.4 and Table 3.1), the port of Milos Island (blue anchor on Figure 3.7), is picked due to its low peak and annual energy demands and the high seasonality of its operations due to the high tourism impact on the island. The implementation of the cold-ironing technique is selected to be applied in this testbed due to the availability of the actual hourly shipping routes and the need to indicate the urgency of implementing RES to small island ports to cover the needs of the cold-ironing technology that will be compulsory for every port worldwide in the near future.

Lastly, the port of Heraklion (red anchor on Figure 3.7) was picked as the ideal case for the optimal of the HRES sizing and the implementation of the SDS due to its high technical and financial status; the port of Heraklion is the biggest port of Crete, being a significant contributor to the island's economy. Besides, the availability of a 10-year timeseries of actual data enables the proper establishment of the custom-made SDS, properly serving the port's needs.

Each port is modelled in 3-D view through the Autodesk Revit software to evaluate the lighting conditions before and after the SOLCS implementation as shown in Figure 3.8.

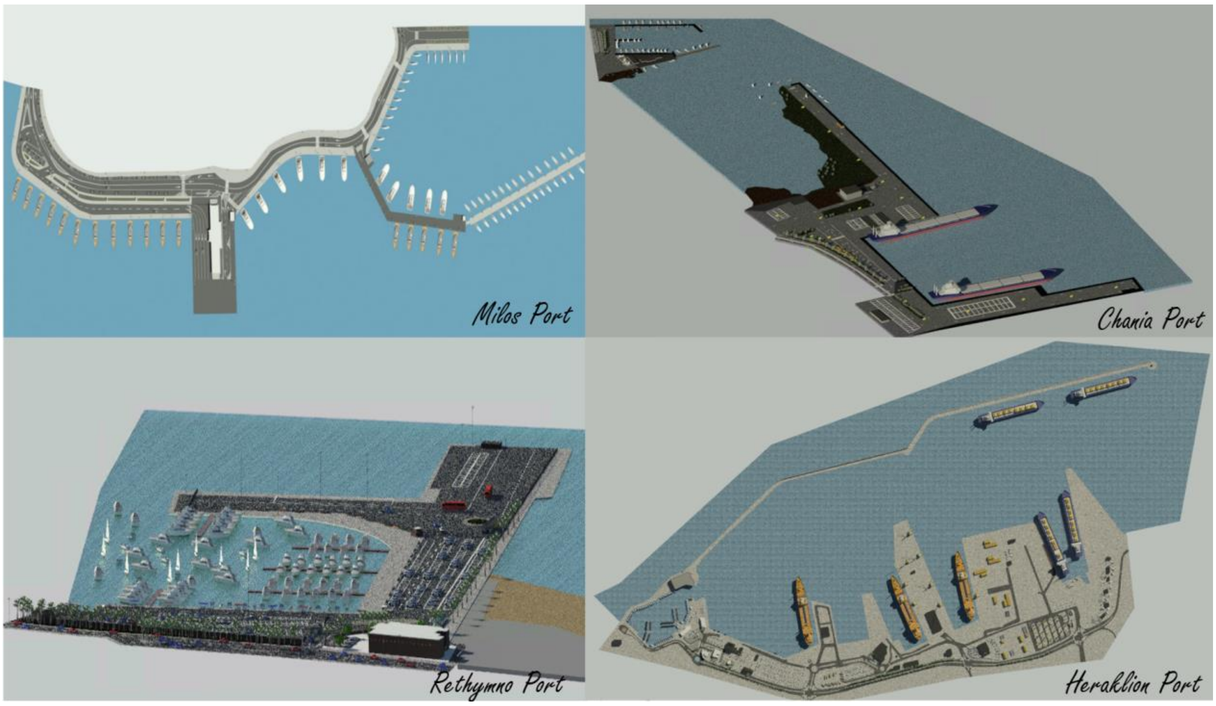


Figure 3.8. 3-D model of each examined case study

4 Forecasting results

4.1. Results outline

The outcomes of the thorough literature review are firstly presented, highlighting the most crucial research gaps and opportunities, providing an interesting approach to the nZEP concept. A summary of the examined techniques and technologies is presented, evaluating each one of them according to three specific criteria. Furthermore, an indicative priority plan for interested port parties is discussed, and a SWOT analysis highlights the overall state of converting a port into nZEP.
Besides, the outcomes of the examined forecasting techniques for the specific case of projecting the Souda's port energy profile for the year 2030 are presented and discussed. The optimal among the established forecasting models is picked to predict future energy consumption, indicating the need to renovate or replace the old-fashioned port's operational techniques and technologies. A statistical analysis accompanies this part of the thesis to indicate and highlight the port's energy profile's main characteristics, pointing areas of interest that may greatly affect port's energy demand and environmental footprint. Finally, the main findings are presented to justify the utility of the study's next steps, pointing out the most appropriate SEMS and RES to be used for its conversion to nZEP.

A complete and balanced generic solution for controlling a port's outdoor lighting infrastructure is presented; the multiplication potential and the replicability are high for other port cases because of the high adaptability of this methodology. Daylight and occupancy are two uncontrollable time-variant parameters that increase the system's complexity due to their unhinged discrepancy throughout the day. According to the daylight illuminance's value and each space's occupancy, the luminaires' dimming levels per space are computed in real-time, and the maximum energy savings are achieved. For safety reasons, even for no occupancy events, the lighting levels are not decreased below 40% of their maximum rated power.

The next subchapter presents the optimal sizing of a port's HRES according to the three sustainability pillars; there is no such initiative in the available literature. The ultimate goal is to propose a comprehensive framework and typology involving the entire process of optimally, in sustainable terms, sizing a port's Hybrid Renewable Energy System (HRES). For the study, actual data are used, resulting in realistic and reliable results. The actual energy demand data and the procurement costs were acquired and processed into a microgrid optimization software (HOMER Pro). Thirty-five total scenarios were assessed on which two types of RES and two types of ESS were examined; two models of VRFB ESS and four models of LA ESS.

After reviewing the most common ESS for such infrastructures, the most environmentally friendly, however the most expensive, is examined. The optimal sizing of a hydrogen energy storage-based HRES is presented next, pointing out the feasibility and the credibility of such a system. Also, to harmonise with the most recent EU legislation, the cold-ironing technology is modelled through the MATLAB software, using actual data, to evaluate the utility of HRES for future ports.

Lastly, after reviewing all the available, well-known and practical solutions towards the renovation and the implementation of green energy generation into ports, two smart energy dispatch strategies for the port's microgrid are established, examined and evaluated. The two micro-grid controllers (dispatch strategies) ensure the whole port's unhampered operation, which has not been investigated in past studies. Concluding, the main goal of this research is to fill the existing gaps of optimal design, sizing and control of an HRES operation into a seaport, completing and rocketing up the concept of nZEP.

4.2. Literature Review outcomes

Table 4.1 summarises the literature's acquired knowledge, the economic and technological maturity of every proposed technology and technique; the latter were grouped into categories regarding their distinctive application area. A clarification of the content of the table is necessary to make it comprehensive:

Economic Maturity: As long as the technology is innovative, the procurement and maintenance costs are high. After the massive production of this specific technology, it becomes much more attractive in terms of affordability and supply.

Technological Maturity: Depends on both the time passed from each technology's first appearance and its implementation into projects along with the problems arisen. We used as criteria the frequency we found each technology in different studies within various sectors.

Experience: It depends on the engineers' know-how in the specific technology and how many times it has been applied to real-life projects. Besides, if it has been in the field for more than five years and some unforeseen problems have arisen, it is registered as a mid-experienced technology.

Table 4.1. Summary of the reviewed techniques and technologies

Application Area	Technology/Technique	Economic Maturity (min: +, max: +++)	Technological Maturity (min: +, max: +++)	Experience (min: +, max: +++)	Prerequisites	Ports that can be applied
Power Supply	Biomass Energy [341,385]	++	++	++	Available resources	National ports International ports
	Wind Energy (Inland - Offshore) [259,386,387]	+++	++	+++	Strong wind potential	All ports
	Photovoltaic Energy [133]	+++	++	+++	Solar potential	All ports
	Tidal farm [138]	+++	++	+++	Strong wind and wave currents	All ports
	Geothermal Energy [63]	++	++	++	Available resources and geothermic capacity	International ports
	Cold-ironing	+++	++	+++	Technical know-how	All ports
	Energy Storage Systems	+	+++	+++	Technical know-how	All ports
Light	Innovative technologies	+++	+++	+++	-	All ports

	Automation sensors [102,388]	+++	++	+++	Technical know-how	All ports
Transportation Vehicles	Electric Vehicles [389]	++	++	++	High-end batteries with sufficient energy capacity	All ports
	Hydrogen Energy [390–392]	+	++	+	Available resources and technical know-how	All ports
	Biofuels	++	+	++	Available biofuel resources	All ports
	Cold-ironing	+++	++	+++	Technical know-how	All ports
Indoor Conditions	HVAC Optimization Systems for Temperature Control [102]	++	++	++	High-end computers and technical know-how	All ports

	Water Heating Systems (Biomass boilers)	+++	+++	++	Available biomass resources	All ports
	Remote control systems	+++	++	+++	High-end computers	National ports International ports
	Efficient hot water use [393]	++	++	+++	Automated boilers, Knowledge of how-to efficient use	All ports
Cargo / Logistics	Automated PCTs [394]	++	++	+++	High-end PCTs and technical know-how	International ports

	Electrification of cargo handling equipment	++	++	+++	High-end batteries with sufficient energy capacity	International ports
	Cold-ironing	+++	++	+++	Technical know-how	All ports
Water quality	Energy-driven seawater pump [265]	+	++	+	Strong wave currents	All ports
Waste management	Innovative environmental-friendly techniques/technologies	+++	++	+++	Meticulous knowledge	All ports
	LCA Analysis of ship waste [29]	++	++	+++	Highly experienced researcher	International ports
	Alternative use of oil waste for generating thermal energy	+++	+++	++	-	National ports International ports

Furthermore, it is proven that the majority of the solutions regarding freight handling equipment are mature enough and fruitful, as long as they have been installed and tested in various ports worldwide. Some solutions seem to be less mature, and the experience is not high enough to ensure safety after installation. For instance, automation may provoke accidents that would not otherwise occur, but this should not be discouraging. The proposed technologies and techniques have many positive side-effects for the ports, such as less traffic congestion and waiting times, contributing to the ultimate goal of diminishing their environmental footprint.

Thus, the critical criteria for nZEP are: (a) air quality, (b) energy conservation and RES, (c) water pollution and water quality, (d) electrification/hybridization of equipment, (e) noise pollution, (f) waste management, (g) SEMS, and last but not least (h) natural habitat quality preservation.

An indicative priority action plan for the port advisors is depicted in Table 4.2. The nZEP approach, as mentioned before, is a dynamic step-by-step process required to achieve the full potential of the nZEP concept; the decision-makers should plan out and implement the appropriate actions, starting from the most mature and economically attractive one.

Furthermore, an Economic Attractiveness–Technological Maturity diagram (EATM) was created to clarify the utility and the availability of the proposed techniques and technologies. It was influenced by the known Importance-Performance Analysis (IPA) concept diagram (Figure 4.1). Table 4.2 and Figure 4.1 further enlighten port authorities' advisors regarding the availability and the affordability of each available technology and technique.

Table 4.2. An indicative plan towards nZEP

Solution/techniques		Time priority		
		Short	Medium	Long
Environmental Management	EE measures on lighting and HVAC systems	X		
	Peak-Shaving / Load Shifting	X		
	Vessels speed reduction		X	
	Virtual Arrival Time			X
	On-shore power supply, cold-ironing	X		
	Electrification/Hybridization of cargo handling equipment		X	
	Automation of PCTs			X
	Automated mooring systems			X
Renewable Energy Systems	Implementation of PV systems		X	
	Onshore WTs	X		
	Floating WTs			X
	Offshore WTs		X	
	Wave energy		X	
	Tidal energy			X
	Geothermal energy			X
	Energy Storage Systems		X	
Alternative/Renewable fuels & waste	LNG, Methanol, Hydrogen			X
	Biomass, Biofuels		X	
	Alternative use of oily Waste	X		

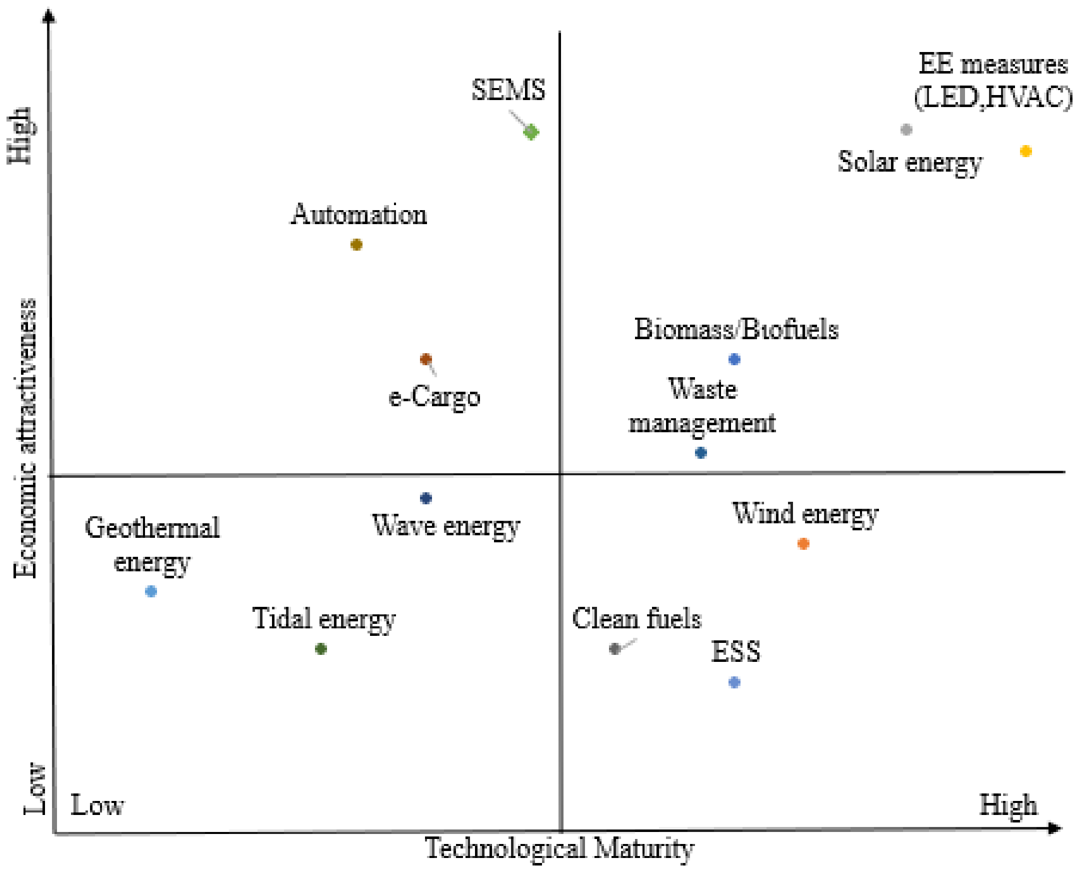


Figure 4.1. EATM diagram of proposed technologies and techniques

As a follow-up, it is clear that the most recommended solutions are the ones on the top-right side of the diagram, such as information and reporting systems, PVs, smart sensors, and the peak shaving technique. On the other hand, the less preferred ones are these on the graph's bottom-left side due to their technological immaturity and cost-effectiveness. A SWOT analysis of the acquired knowledge's synthesis was conducted, further supporting the efficient plan of moving towards sustainability (Figure 4.2).

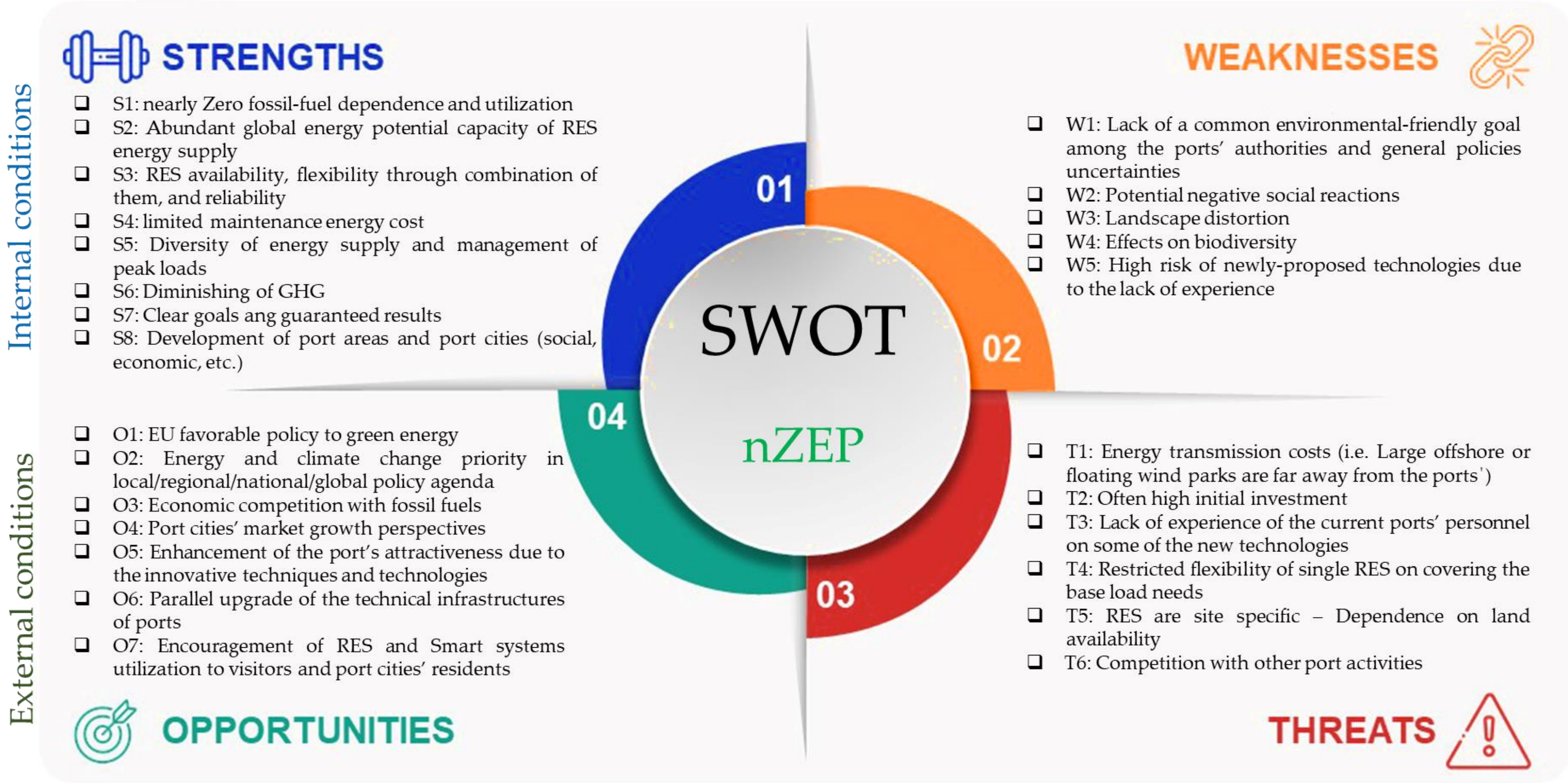


Figure 4.2. SWOT analysis diagram for the nZEP concept (Source: Authors)

So, what ports should do to move towards the nZEP concept and decarbonise themselves is to build on their strengths, boost their weak areas, head off the possible threats, and efficiently exploit every upcoming opportunity. For example, the high initial capital for such investments can be funded by public or private investors. The ports’ personnel can also be informed, educated, and trained in these fresh-new technologies and techniques. In this way, the weaknesses would be eliminated, and the concept could be more viable and realistic than ever. Conditions are favourable for port authorities, as the EU is promoting and funding such incentives. Not only the port's social acceptance would be enhanced, and the ports’ infrastructures will be renovated, but also ports can be the paradigm for port cities’ inhabitants towards a more sustainable future. However, technologies with low expertise should be avoided, for the time being, to eliminate the possibility of harming the operations' stability and reliability. Figure 7 can be a comprehensive guide for every port authority to organise and design its sustainable business plan.

4.3. Statistical analysis and future projections

In this subchapter, the results of the forecasting models are presented. The models were created based on hourly, daily, and monthly data from 2015 to 2019, including meteorological data from the National Observatory of Athens (NOA) and NASA's POWER database. The MSE and RMSE indices were calculated for comparison purposes among the created models. The optimal among them are picked and used to calculate the 2030 port's energy demand profile. Finally, the annual projections of all the models areshown .

4.3.1. Hourly Data

The results of the linear regression models (LR), artificial neuronal networks (ANN), and machine learning algorithms (ML), based on the hourly meteorological and energy data, are presented and discussed in this section.

4.3.1.1. Hourly Linear Regression Model (H-LR) and Pearson Correlation factors

After constructing the linear regression model, the following equation 79 is created. The equation's variables are presented in Table 4.3.

$$Y = 175.2 + 0.000759 \times X_1 + 0.175 \times X_2 + 0.9159 \times X_3 + 0.2378 \times X_4 - 1.1737 \times X_5 + 0.1313 \times X_6 - 6.20 \times X_7 - 0.1348 \times X_8 - 0.079385 \times X_9 \quad (79)$$

Table 4.3. Linear regression model variables

Terms	Data	Terms	Data
Y	Electricity (kWh)		
X_1	Timestep	X_6	Pressure (hPa)
X_2	Time	X_7	Precipitation (mm)
X_3	Temperature ()	X_8	Wind speed (km/h)
X_4	Humidity (%)	X_9	Solar Radiation (W/m^2)
X_5	Dew Point (℃)		

The linear regression model's outcomes are statistically significant as the P-value is lower than 0.05. Also, all the equation variables have P-values lower than 0,05, which indicates that these variables are statistically significantly related to the response variable. In addition, the conditions for the linear regression modelling are met; the Durbin-Watson coefficient (0,38) is lower than 4.0.

Table 4.4 shows the correlation factors among the predictor variables and the response variable. Solar radiation (X_9) and energy demand are negatively connected, as expected, because the primary energy consumption of the port is due to the outdoor lighting infrastructures. To further investigate the above observation, a variable is generated on whether it is a day or night (TimeOfDay) based on the hour - from 7:00 AM to 6:00 PM, it is considered as day-hour from 7:00 PM up to 6:00 AM is considered as night-hour. The One-way ANOVA analysis was used to explore the relevance of whether it is day-hour or night-hour in the energy demand; the F-value is relatively high (71.494), meaning that there is a significant difference between day and night energy demand. Since there is a significant difference in these mean levels, two multi-comparison tests (Tukey's and Fisher's LSD) were executed for the energy demand; proving that the energy demand among the day and night hours are significantly different (p-values=0.000).

Table 4.4. Pairwise Pearson Correlation Factors for the hourly data

Variable	Correlation to Y	95 % CI for p	p-value
X_1	0.272	(0.264; 0.281)	0.000
X_2	-0.571	(-0.577; -0.565)	0.000
X_3	-0.312	(-0.321; -0.304)	0.000
X_4	0.316	(0.308; 0.325)	0.000
X_5	-0.172	(-0.181; -0.163)	0.000
X_6	0.014	(0.004; 0.023)	0.004
X_7	0.035	(0.025; 0.044)	0.000
X_8	-0.224	(-0.233; -0.215)	0.000
X_9	-0.45	(-0.457; -0.442)	0.000

Temperature and humidity variables (X_3, X_4) have a statistically significant correlation to the energy demand due to the high seasonality. The weak negative correlation of wind speed (X_8) with the port's energy demand is explained by the fact that ships do not travel in high or extreme wind events. On the other hand, there is a weak, almost non-existent, correlation between atmospheric pressure and precipitation (X_6, X_7) as they do not particularly affect the operation of the external lighting of the port.

The hourly linear regression model (H-LR) has a $MSE = 680{,}08\, kWh^2$ and $RMSE = 26{,}08\, kWh$. Also, the model's errors range from -50 kWh up to 50 kWh, which indicates that the model is not perfectly adapted to the data. Figure 4.3 presents the average hourly energy profile according to the H-LR model for 2015-2019, where it seems to be following the seasonality and the hourly fluctuation but not the actual energy values.

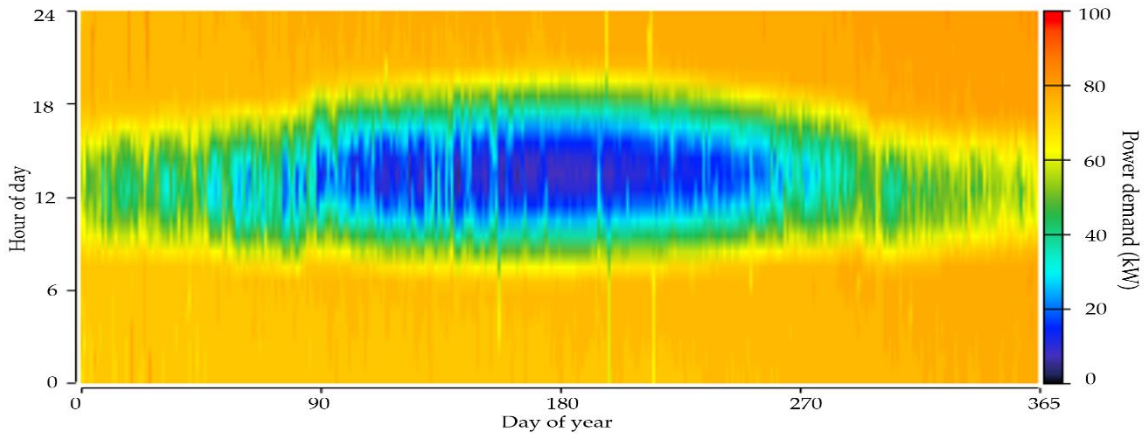


Figure 4.3. The average hourly energy demand of the H-LR model for the years 2015-2019

4.3.1.2. Hourly Artificial Neural Networks Model (H-ANN)

The optimal model was established based on the actual data, through the test and error method, as there is no exact technique for creating artificial neural networks, calculating the number of hidden layers, or the number of neurons on the hidden layer and due to the restrictions of the Neural Net Fitting App of MATLAB software. The data were randomly separated (dividerand) as follows:

- 70% for training
- 15% for validation
- 15% for testing

Levenberg-Marquardt (trainlm) was selected as the training method incorporating:

- a hidden layer with a tan-sigmoid (tansig) transfer equation with 27 neurons,
- an output layer with a pure-linear transmission equation (purelin), and one neuron.

The model is well adapted to the actual data and predicts the energy demand with an MSE=74,83 kWh^2 and RMSE=8,65 kWh^2. Figure 4.4 presents the average hourly energy profile according to the H-ANN model for 2015-2019, where it seems to be following the reality; it seems to fit perfectly to the actual data.

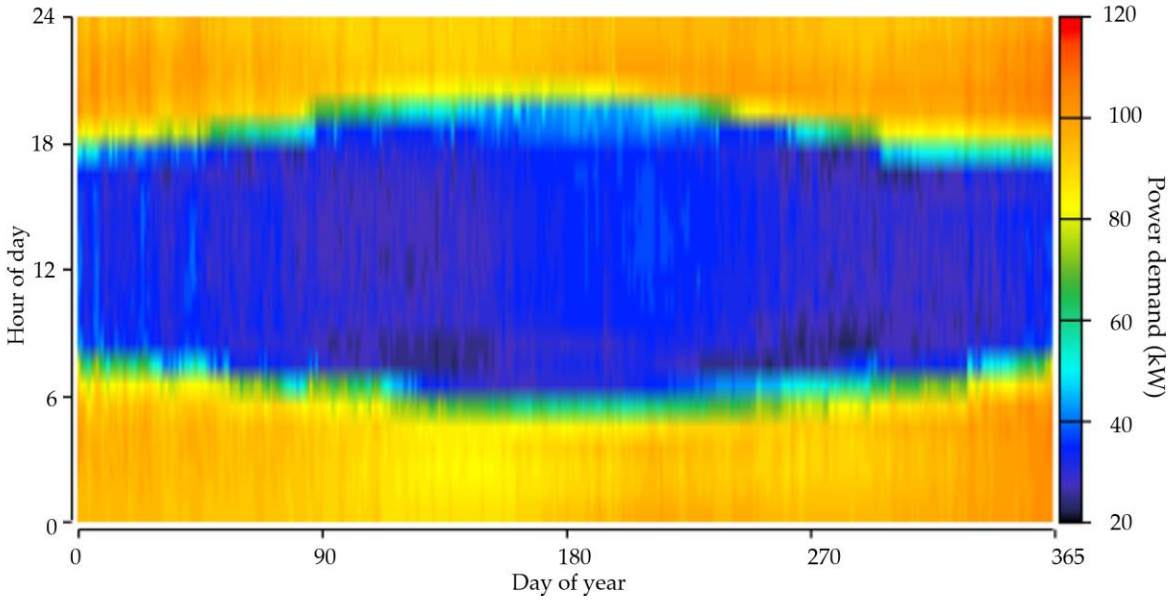


Figure 4.4. Average hourly H-ANN model's energy demand for the years 2015-2019

4.3.1.3. Hourly Machine Learning Model (H-ML)

The 5-fold test's outcomes were satisfactory enough, so the 10-fold was not examined. The used techniques' outcomes are summarised in Table 4.5 based on the root of each technique's average square error.

Table 4.5. Machine learning models' RMSEs for the hourly data.

ML Technique-Model	RMSE	ML Technique-Model	RMSE
Exponential GPR	2.21	Bagged Trees	5.20
Optimizable	3.00	Coarse Tree	6.82

Ensemble			
Optimizable Tree	3.23	Fine Gaussian SVM	6.91
Fine Tree	3.23	Mattern 5/2 GPR	9.38
Medium Tree	4.89	Rational Quadratic GPR	9.40

Exponential GPR is the optimal model to predict the hourly energy demand, according to the RMSE index for the hourly data.

The H-ML model has an $\mathrm{MSE} = 4{,}86\ \mathrm{kWh}^2$ and an $\mathrm{RMSE} = 2{,}21\ \mathrm{kWh}$. The H-ML model is well adapted to the data. Figure 4.5 shows the average energy demand profile of the model for the years 2015-2019, being relatively close to the actual values.

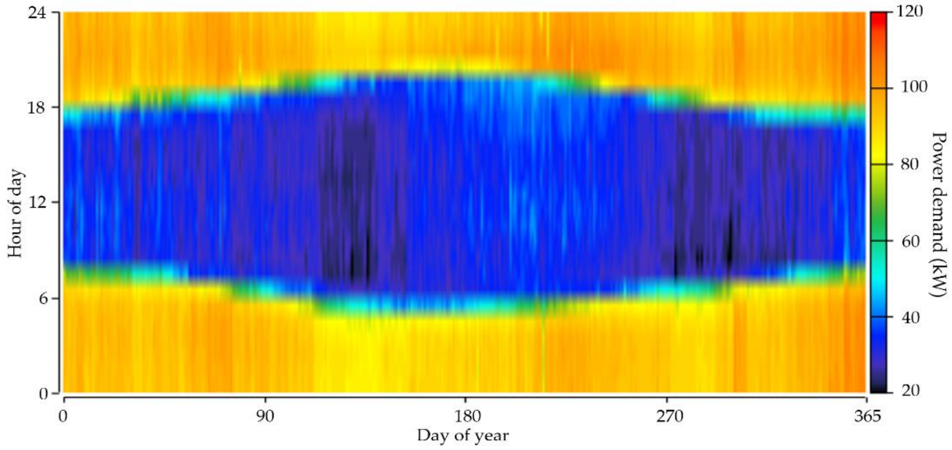


Figure 4.5. Average hourly H-ML model's energy demand for the years 2015-2019

4.3.1.4. Comparison of the hourly models

The hourly models' major characteristics are compared in

Table 4.6.

Table 4.6. Comparison of the hourly models

Model	MSE	RMSE	R^2
H-LR	680.06 kWh^2	26.08 kWh	0.45
H-ANN	74.83 kWh^2	8.65 kWh	0.94
H-ML	4.86 kWh^2	2.21 kWh	0.99

The H-ML has better MSE and R^2 than the other two. The H-LR does not follow the actual average hourly demand profile. On the contrary, the H-ANN and the H-ML models are accurate in their predictions;, the optimal hourly model is the H-ML.

4.3.2. Daily data

The results of the linear regression models (LR), artificial neuronal networks (ANN), and machine learning algorithms (ML), based on the daily meteorological and energy data, are presented and discussed in this section. The month is added as a variable to the data.

4.3.2.1. Daily Linear Regression (D-LR)

The equation derived from the daily linear regression model is the following. The variables of the model are presented in Table 4.7.

$$Y = 755 + 0.019226 \times X_1 - 0.128 \times X_2 + 9.6 \times X_3 - 2.0 \times X_4 + 0.43 \times X_5 - 11.5 \times X_6 + 0.63 \times X_7 + 419 \times X_8 + 0.30 \times X_9 - 0.6335 \times X_{10} \quad (80)$$

Table 4.7. Daily Linear Regression terms

Variable	Data	Variable	Data
Y		Electricity (kWh)	
X_1	Timestep	X_6	Dew Point (°C)
X_2	Day	X_7	Pressure (hPa)
X_3	Month	X_8	Precipitation (mm)
X_4	Temperature ()	X_9	Wind speed (km/h)
X_5	Humidity (%)	X_{10}	Solar Radiation (W/m^2)

The linear regression model is of statistical significance as the p-value is lower than 0.05. In addition, the terms time step (X_1), precipitation (X_8), and solar radiation (X_{10}) have p-values < 0.05, indicating that these variables have a statistically significant correlation with the response variable. Concerning other variables with a P-value > 0.05, they could be removed without significantly affecting the model as they appear to be interrelated with other or other existing variables. Furthermore, the linear regression modelling conditions are met; the Durbin-Watson coefficient (0.26) is lower than 4.0.

The daily linear regression model (D-LR) has an $MSE = 34{,}987.57\ kWh^2$, and an $RMSE = 187.05\ kWh$. Figure 4.6 illustrates the model's energy profile compared to the actual one; the model outcomes do not adequately fit the actual values.

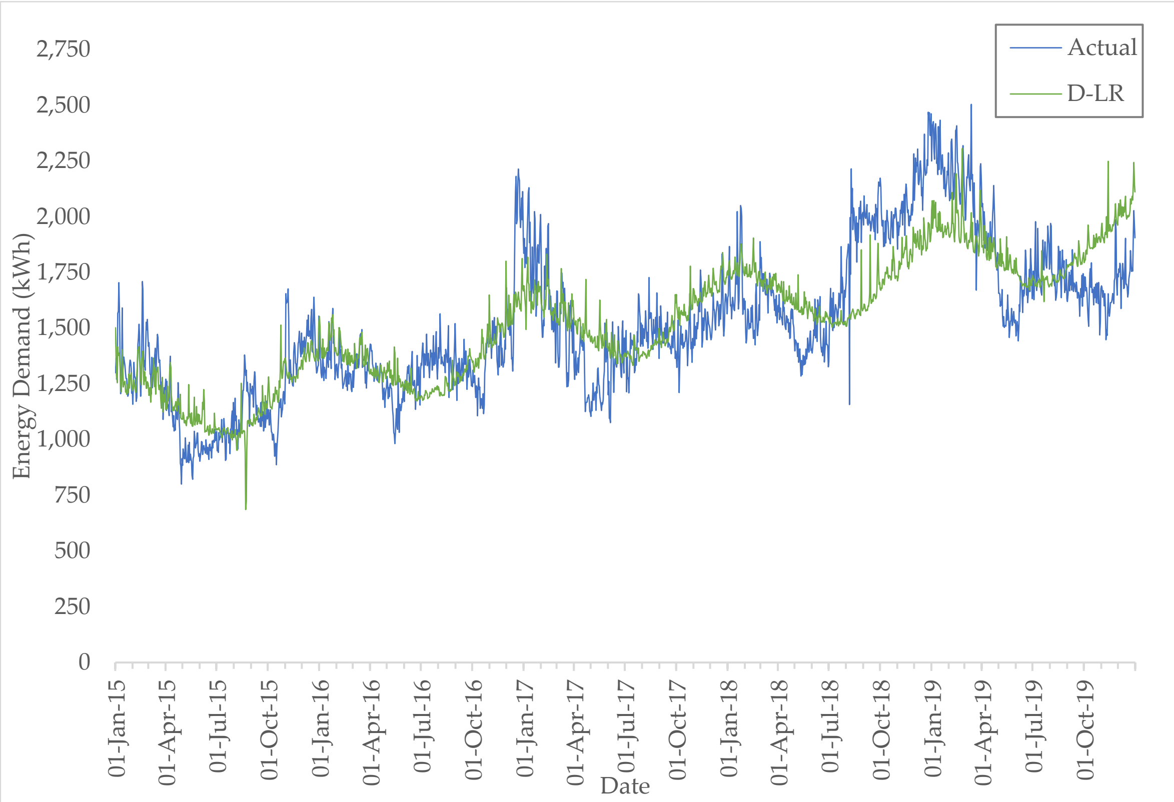


Figure 4.6. Daily energy demand profile of the D-LR model compared to the actual

4.3.2.2. Daily Artificial Neural Networks Model (D-ANN)

In the D-ANN model, the data were randomly separated (dividerand) as follows:

- 70% for training
- 15% for validation, and
- 15% for testing

Levenberg-Marquardt (trainlm) was selected as the training method incorporating:

- a hidden layer with a tan-sigmoid (tansig) transfer equation with 11 neurons, and
- an output layer with a pure-linear transmission equation (purelin), and one neuron

D-ANN model has a $MSE = 9{,}456.02\ kWh^2$, and a $RMSE = 97.24\ kWh$. The model appears to be well adapted to the data, as Figure 4.7 indicates.

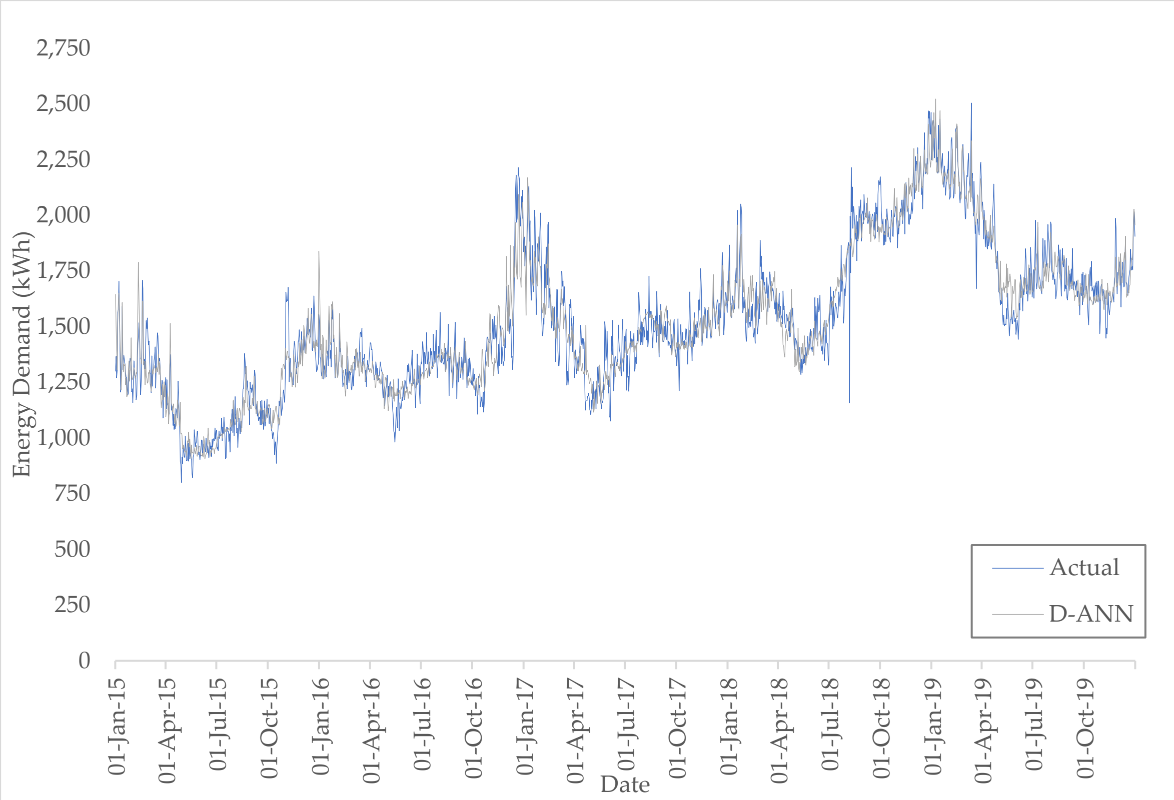


Figure 4.7. The daily energy demand of the D-ANN model compared to the actual

4.3.2.3. Daily Machine Learning Model (D-ML)

The 5-fold tests' outcomes were satisfactory in the daily data analysis, so 10-fold tests were avoided. The examined models' results are summarised in Table 4.8 based on the root of each technique's average square error.

Table 4.8. Machine learning models' RMSEs for the daily data

ML Technique-Model	RMSE	ML Technique-Model	RMSE
Optimizable GPR	29.79	Bagged Trees	104.11
Optimizable Ensemble	85.06	Coarse Tree	109.81
Optimizable Tree	96.96	Boosted Trees	116.83
Medium Tree	97.712	Rational Quadratic GPR	124.45
Fine Tree	102.04	Exponential GPR	124.65

Exponential GPR is the optimal forecast model to calculate the daily energy demand, according to the RMSE index. The D-ML model has a $R^2 = 0.95$, a $MSE = 887.49\ kWh^2$ And a $RMSE = 29.79\ kWh$. According to Figure 4.8, the D-ML model is sufficiently well adapted to the actual data.

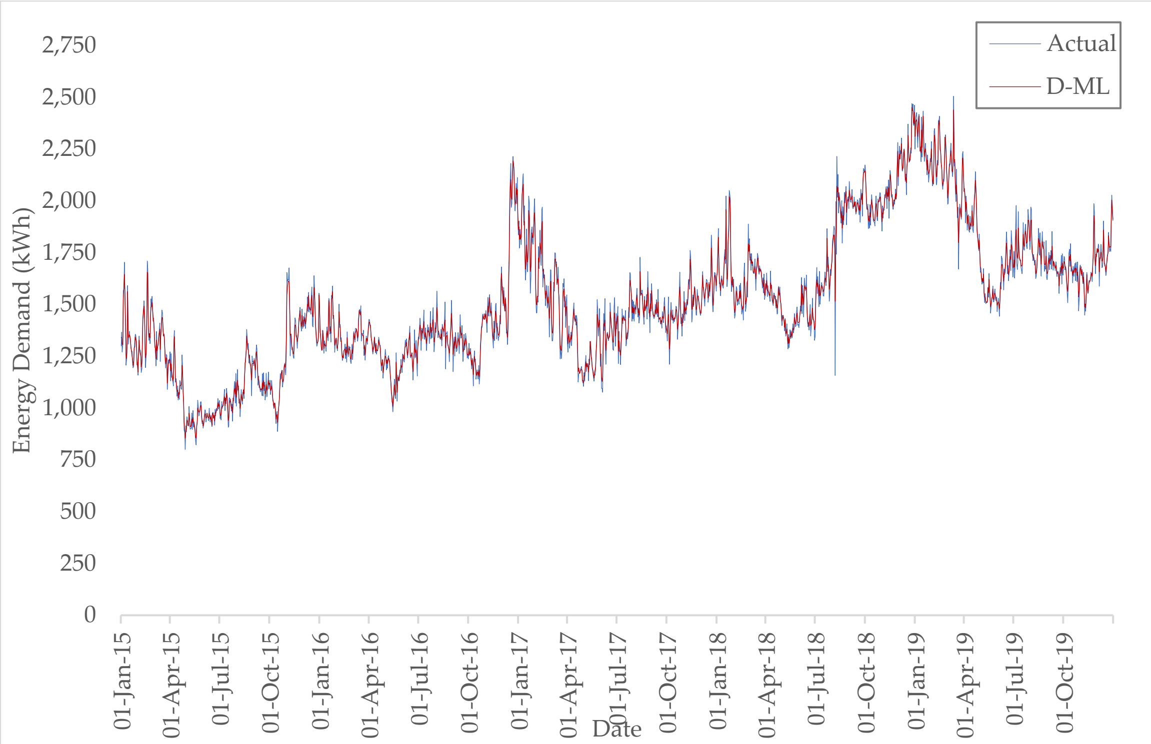


Figure 4.8. The daily energy demand of the D-ML model compared to the actual

4.3.2.4. Comparison of the daily models

The daily models' major characteristics are compared in Table 4.9.

Table 4.9. Comparison of the daily models

Model	MSE	RMSE	R^2
D-LR	34,987.57 kWh^2	187.05 kWh	0.67
D-ANN	9,456.02 kWh^2	97.24 kWh	0.90
D-ML	887.49 kWh^2	29.79 kWh	0.95

The D-ML has better MSE and R^2 than the other two. The D-LR does not accurately predict the actual average hourly demand profile. On the contrary, the H-ANN and the H-ML models are accurate in their predictions. Thus, the optimal hourly model is the H-ML.

4.3.3. Monthly data

For the monthly data, more models were created due to the lower complexity and lower computational load. Specifically, an LR, an ANN, an ML, a time series breakdown (Decomposition) (TMD), and the Box-Jenkins ARIMA model are listed in order.

4.3.3.1. Monthly Linear Regression Model (M-LR)

The equation derived from the monthly linear regression model is the following. The variables of the model are presented in Table 4.10.

$$Y = 307{,}413 + 0.5494 \times X_1 - 102 \times X_2 + 1{,}673 \times X_3 - 663 \times X_4 + 1{,}432 \times X_5 - 198 \times X_6 + 132{,}600 \times X_7 - 806 \times X_8 - 38.2 \times X_9 \quad (81)$$

Table 4.10. Monthly Linear Regression terms

Terms	Data	Terms	Data
Y	Electricity (kWh)		
X_1	Timestep	X_6	Pressure (hPa)
X_2	Time	X_7	Precipitation (mm)
X_3	Temperature ()	X_8	Wind speed (km/h)
X_4	Humidity (%)	X_9	Solar Radiation (W/m^2)
X_5	Dew Point (°C)		

The linear regression model is of statistical significance as the p-value is less than 0.05. Only the variables of the time step (X_1) and precipitation (X_7) are statistically significant (p-values<0.05). The Durbin-Watson coefficient (1.06) is lower than 4.0, enabling the utilization of this technique.

The M-LR model has an $\text{MSE} = 22{,}474{,}064.04\ \text{kWh}^2$ and an $\text{RMSE} = 4{,}740.68\ \text{kWh}$. According to Figure 4.9, the model's values follow the increasing trend but do not fit the model appropriately, meaning that the model does not qualify as trustworthy.

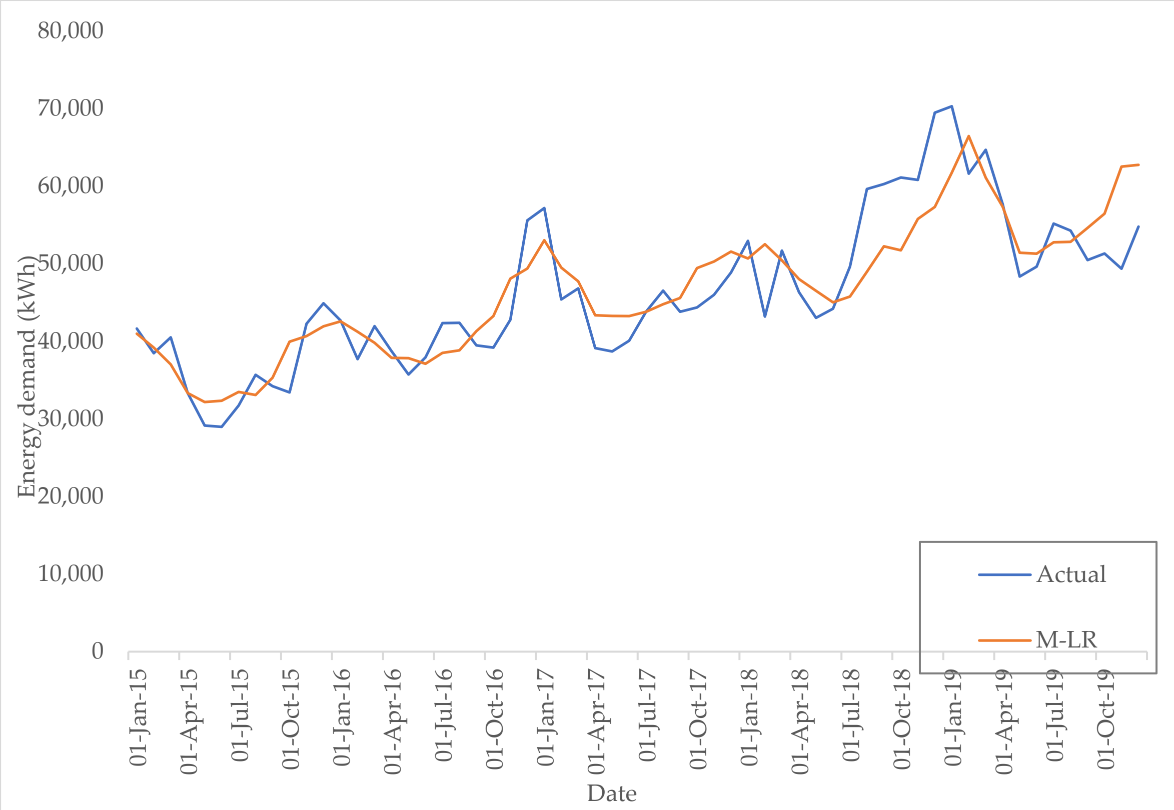


Figure 4.9. The daily energy demand of the D-ML model compared to the actual

4.3.3.2. Monthly Artificial Neural Networks Model (D-ANN)

In the M-ANN model, the data were randomly separated (dividerand) as follows:

- 50% for training
- 25% for validation, and
- 25% for testing

Levenberg-Marquardt (trainlm) was selected as the training method incorporating:

- a hidden layer with a tan-sigmoid (tansig) transfer equation with nine neurons, and
- an output layer with a pure-linear transmission equation (purelin), and one neuron

M-ANN model has an $\text{MSE} = 66.104.306{,}70\ \text{kWh}^2$ and an $RMSE = 8.130{,}46\ \text{kWh}$. Although the model, initially, appears to be well adapted to the data, as Figure 4.10 indicates, since 09/01/2018, the model calculates two significant outliers but, generally speaking, the model follows the increasing trend of the energy consumption.

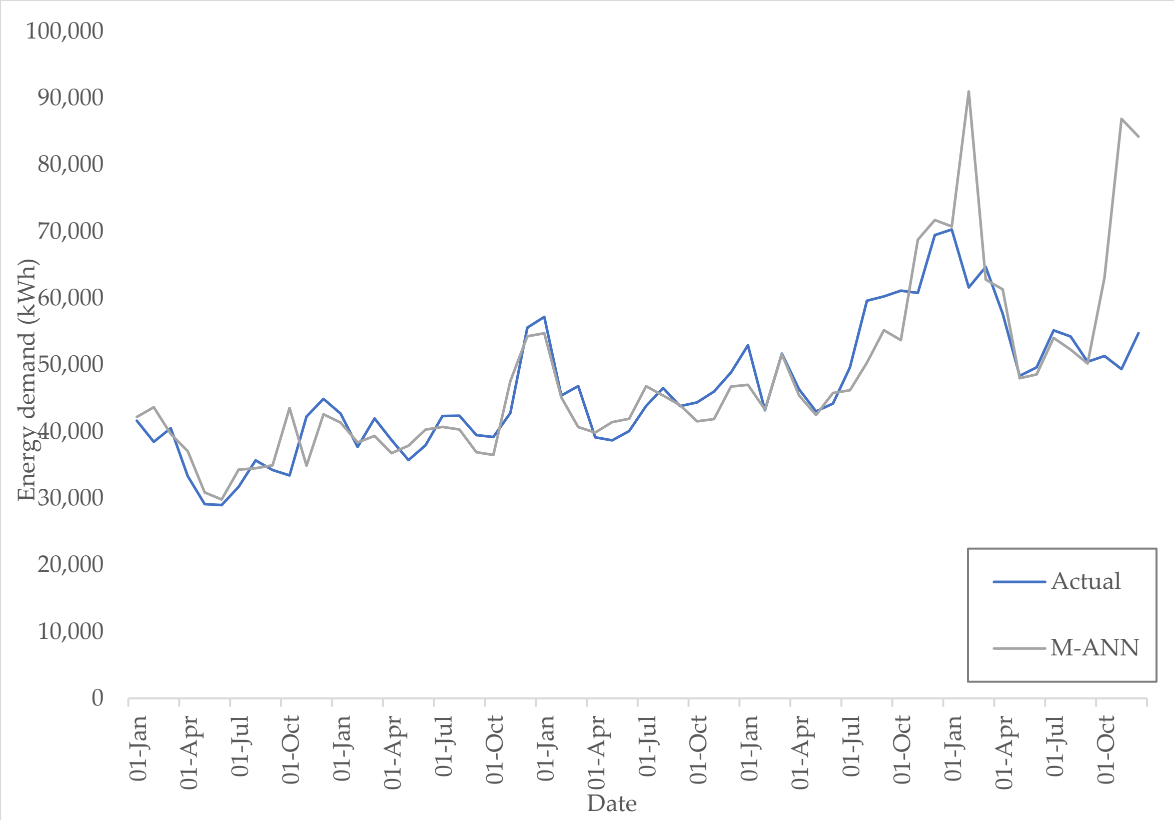


Figure 4.10. The monthly energy demand of the M-ANN model compared to the actual

4.3.3.3. Monthly Machine Learning Model - (M-ML)

Because it was reasonably low, the monthly data eventually needed to be divided into 10-fold sections for training, validation, and testing. The results of the used ML techniques are summarised in Table 4.11.

Table 4.11. Machine learning models' RMSEs for the monthly data

ML Technique-Model	RMSE	ML Technique-Model	RMSE
Optimizable GPR	3.439,1	Fine Tree	5.218,1
Optimizable Ensemble Trees	4.278,3	Exponential GPR	6.220,7
Optimizable Tree	4.278,3	Medium Tree	5.657,3
Linear SVM	4.957,1	Medium Gaussian SVM	5.778,3
Boosted Trees	4.977,1	Linear Regression	5.786,3

Optimizable GPR is the optimal model to predict the monthly energy demand, according to the RMSE index.

Although some of the examined ML models had low RMSE, they did not provide valid forecasts for 2030 (low or even negative values). The optimal model was the Linear SVM technique's one, providing satisfactory monthly forecasts for 2030. The M-ML model has a $R^2 = 0.66$, an $MSE = 24{,}572{,}705.05\ kWh^2$, and an $RMSE = 4{,}957.09\ kWh$. Figure 4.11 shows that the model does not accurately fit the actual data, although it follows the increasing energy consumption trend.

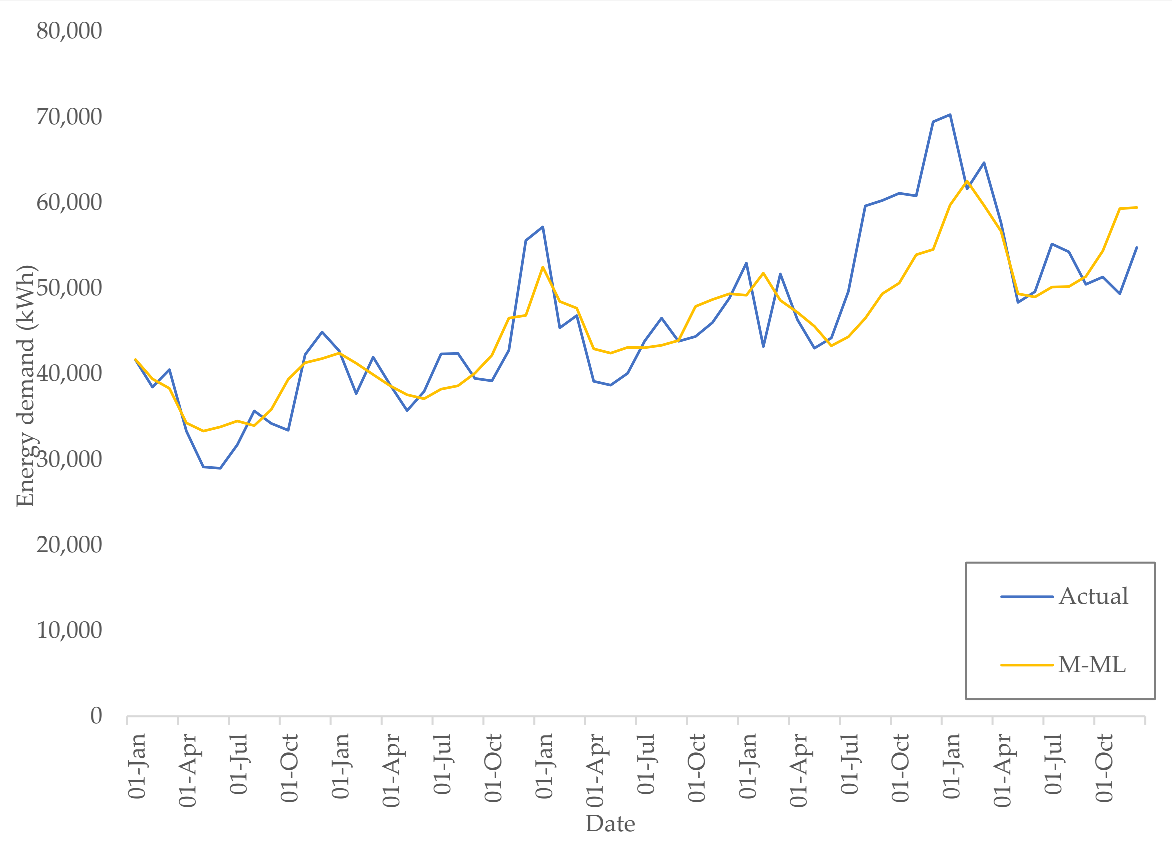


Figure 4.11. Monthly energy demand of the M-ML model compared to the actual

4.3.3.4. Time Series Decomposition Model - (M-TMD)

The additive (additive) model is used for the time-series decomposition model because of the data's trend and seasonality which are added behind each other, implied by the fact that seasonality does not drastically alter.

The equation is the following, and the breakdown data are shown in Figure 4.12.

$$Yt = 33{,}673 + 415.6 \times t \quad (22)$$

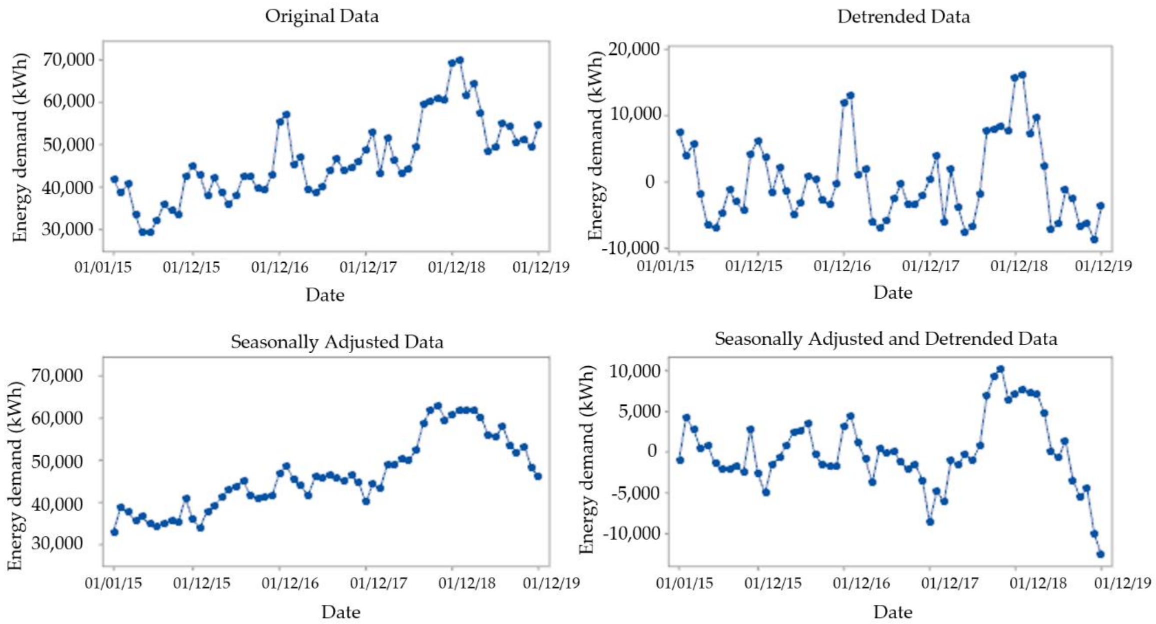


Figure 4.12. Breakdown of the monthly energy demand time series data.

The TMD model has an $\mathrm{MSE} = 19{,}460{,}260.52\ \mathrm{kWh}^2$ and an $\mathrm{RMSE} = 4{,}411.38\ \mathrm{kWh}$. Figure 4.13 proves that the model's values follow the trend of the actual ones but do not adequately fit them.

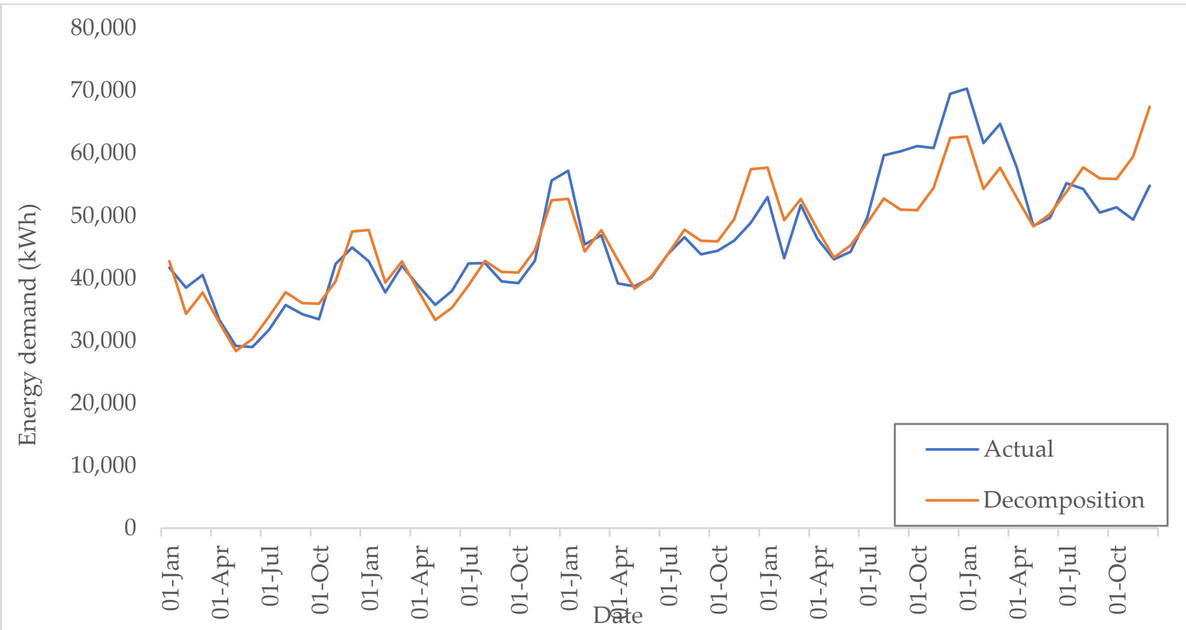


Figure 4.13. The monthly energy demand of the TMD model compared to the actual

4.3.3.5. Box-Jenkins Method - Self-Regression ARIMA (SARIMA)

The monthly data are handled in R-studio via the auto.arima() function uses a stepwise approach to look for multiple combinations of p,d,q parameters and selects the best model with the least AIC (Akaike Information Criteria). The AIC quantifies the degree of adaptation and simplicity/economy of the model in a single statistic. The resulting model is ARIMA (1,0,0) (1,1,0) with d=1 (drift); in short, the model is renamed SARIMA.

Figure 4.14 reflects the forecasted energy profile of the SARIMA model for the years 2015-2019 relative to the actual; the model follows the growth trend and the seasonality of energy consumption.

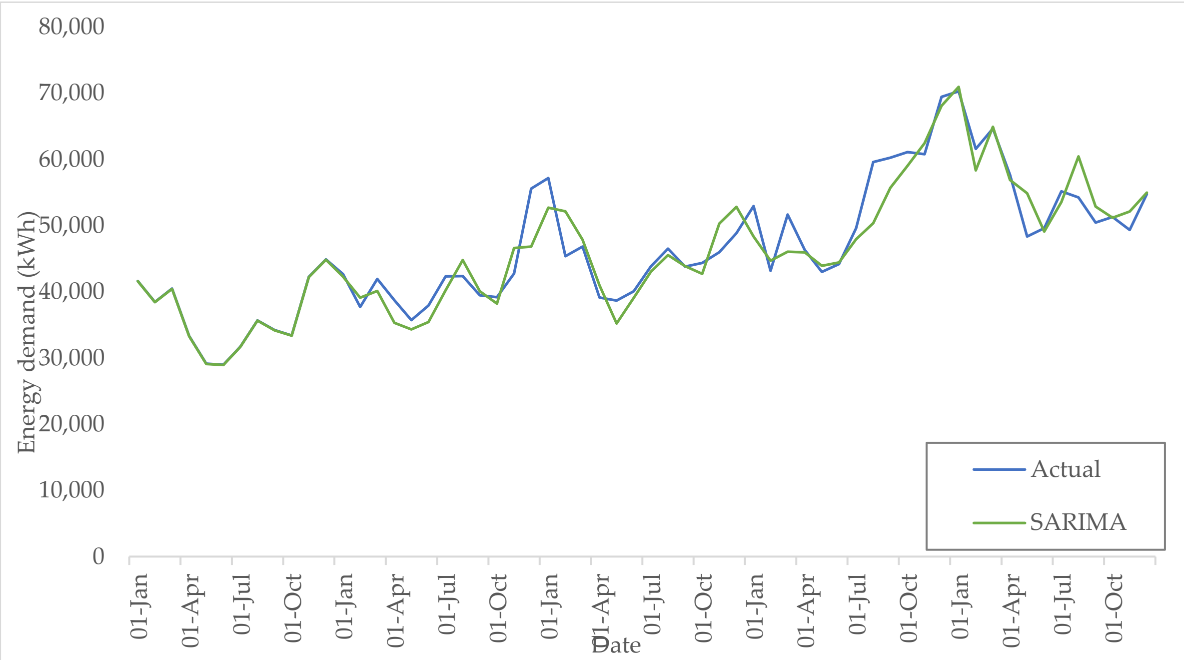


Figure 4.14. Monthly energy demand of the SARIMA model compared to the actual

4.3.3.6. Comparison of the monthly models

The monthly models' major characteristics are compared in Table 4.12.

Table 4.12. Comparison of the monthly models

Model	MSE	RMSE
M-LR	22,474,064.04 kWh^2	4,740.68 kWh
M-ANN	66,104,306.70 kWh^2	8,130.46 kWh
M-ML	24,572,705.05 kWh^2	4,957.09 kWh
DM	19,460,260.52 kWh^2	4,411.38 kWh
SARIMA	8,899,430.38 kWh^2	2,983.19 kWh

The SARIMA model has the best $MSE = 8{,}899{,}130.38\ kWh^2$, while the TMD model follows ($MSE = 19{,}460{,}260.52\ kWh^2$). Then comes the M-LR with $MSE = 22.747{,}064.04\ kWh^2$, the M-ML with $MSE = 24{,}572{,}705.05\ kWh^2$, and finally the M-ANN with $MSE = 66{,}104{,}306.70\ kWh^2$.

4.3.4. Forecasts of the Souda port's energy profile in 2030

This sub-section initially presents the energy profile of the port for the year 2030, using the best model (H-ML). The results of the second-best forecasting model (H-ANN) are presented afterwards. Finally, all the examined models' annual energy demand values are presented to evaluate the performance of all the used methods.

4.3.4.1. Energy profile forecast for 2030 based on the H-ML model

The hourly H-ML machine learning model of the Exponential Gaussian Process predicted that the hourly electricity consumption for the year 2030 is expected to be between 61.86 kWh and 160.44 kWh, with an average hourly energy demand of 117.31 kWh. Figure 4.15 demonstrates the expected hourly Souda port's hourly energy profile for 2030.

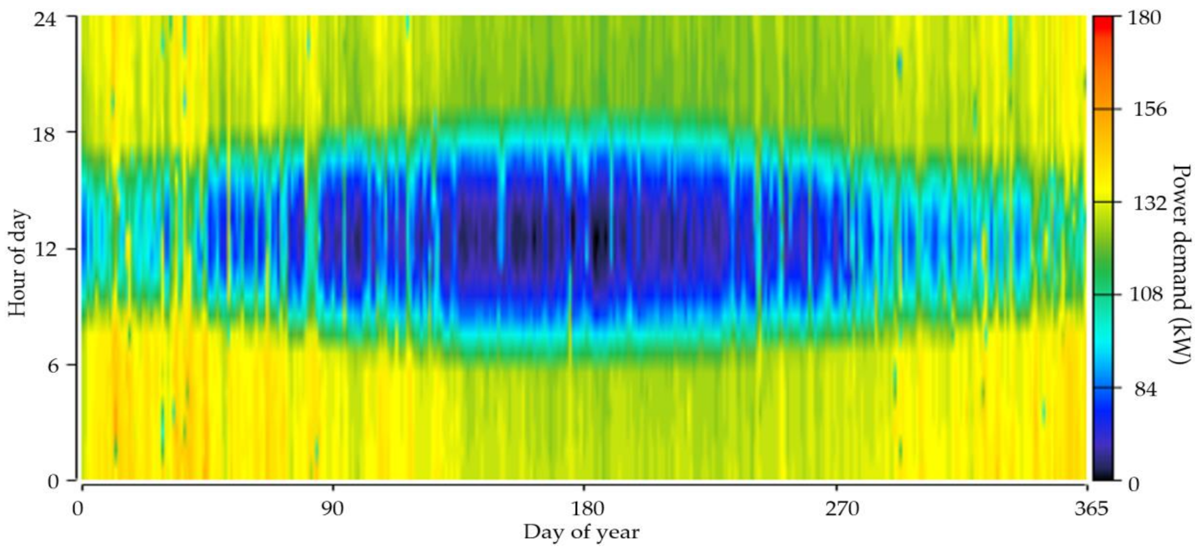


Figure 4.15. Hourly energy demand forecast for 2030 according to the H-ML model

Finally, the annual energy demand for 2030 according to the H-ML model will be 1,027,649.94 kWh. The increasing trend in energy demand due to the economic-social growth is being followed, thereby creating significant higher energy demand in the coming years.

4.3.4.2. Energy profile forecast for 2030 based on the H-ANN model

According to the H-ANN model, Figure 4.16 reflects the expected hourly energy demand profile of the port of Souda for the year 2030. The energy demand is higher during night hours.

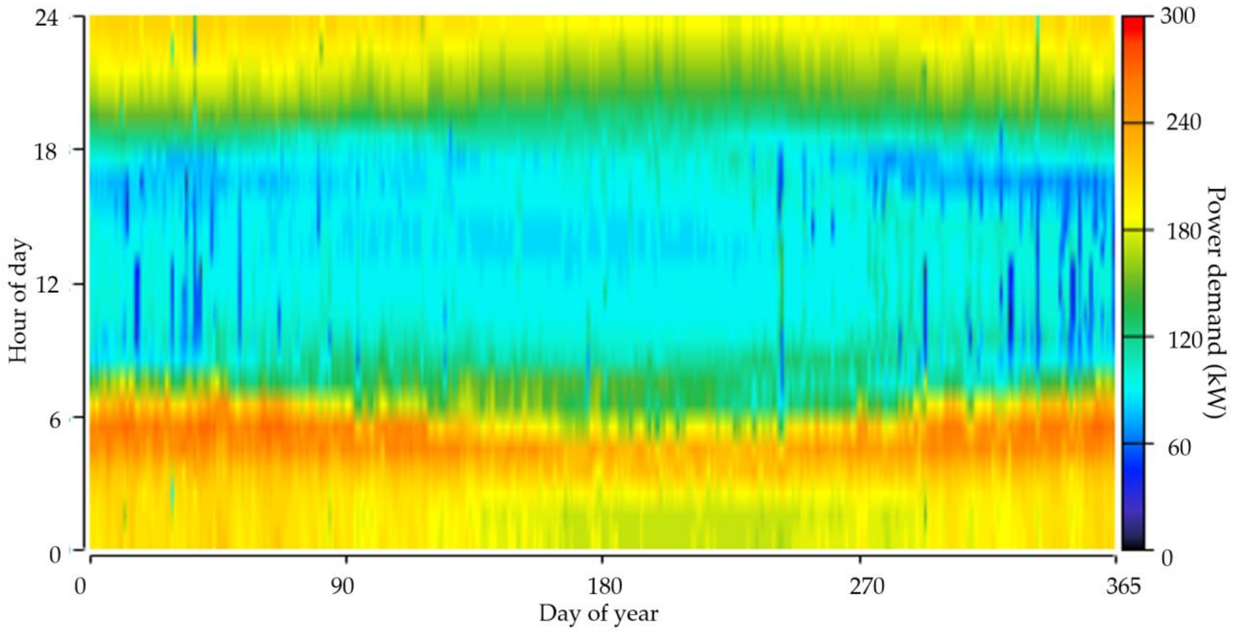


Figure 4.16. Hourly energy demand forecast for 2030 according to the H-ANN model

The annual electricity consumption for 2030 according to the H-AN model will be 1,314,292.45 kWh. Compared to the H-ML model, the H-ANN model's forecasts have significantly higher values, by approximately 300,000 kWh/year.

4.3.4.3. Annual models' forecasts for 2030

Figure 4.17 shows the annual projections of all the used models for 2030.

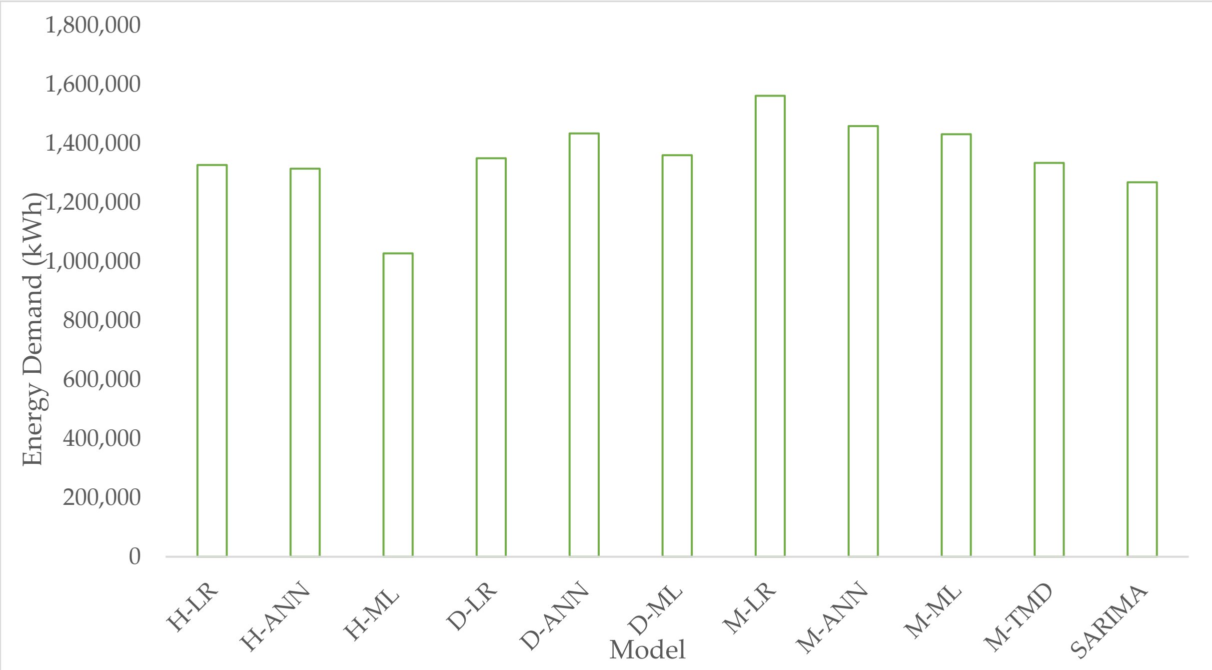


Figure 4.17. Annual energy demand forecast of all the examined models for 2030

According to Table 4.13, the models' forecasts are all relatively close; the forecast of the M-LR model has the highest annual energy demand (1,561,356.12 kWh), while the lowest projection (1,027,649.94 kWh) represents the H-ML model.

Table 4.13. Annual energy demand for all the examined models

Model	Electricity (kWh)	Model	Electricity (kWh)
H-LR	1,326,974.50	M-LR	1,561,356.12
H-ANN	1,314,292.45	M-ANN	1,459,066.88
H-ML	1,027,649.94	M-ML	1,431,339.81
D-LR	1,349,941.54	DM	1,334,146.27
D-ANN	1,433,603.20	SARIMA	1,268,388.70
D-ML	1,359,814.69		

5 Case studies from technologies for the transition of ports into nZEP

Ports have a fishing village's or town's characteristics; there are roads, pavements, green areas, administrative buildings, and docks. Towards the nZEP vision, a step-by-step procedure is to be followed to transit from a conventional port to a contemporary infrastructure. The first step towards a sustainable port is to reduce its energy demand by diminishing the current energy wastes through the implementation of SEMS.

After statistically analysing and examining the big actual energy data of the four-port case studies, the outdoor lighting infrastructures are proved to be the most energy-demanding operation for all the cases’ operations. Specific subspaces need to be more illuminated than others due to the current legislative limits. Docks or passenger areas require high illuminance levels to properly handle their services, being more energy-demanding than others for safety reasons. Due to the different legislative limits and variations of various subspaces' illuminance levels, they can be considered building zones. The research team established a totally new methodology for controlling the outdoor lighting of port areas, suggesting a SOLCS tool for a medium-sized port, the port of Rethymno; such smart tools feature high versatility as they can be replicated in other lighting applications.

After examining and evaluating the fruitful implementation of a SEMS and reducing the energy demand, the implementation of RES and ESS is the next step. Several HRES for a medium-sized port (Souda port, Chania) are conceptualised, simulated, discussed, compared, and evaluated to pick the optimal among them. The suggested HRES comprises PVs, WTs, and different types of ESS. The most viable and reliable HRES solutions are selected and placed into a candidate pool. Finally, the optimal one is picked for each of the three sustainability criteria set by the research team. The port of Chania was picked as the ideal case study to be presented in this section due to the high reliability and replicability of the study's outcomes, as discussed below.

The next step after implementing an HRES is implementing a future EU regulation that every port will be forced to adapt. The cold-ironing technology is integrated and examined to eliminate berthing ships' emissions harmonised with the most recent EU legislation. The port of Milos was selected as the most favourable, among the available cases, testbed due to its small size and its high seasonal operational fluctuation due to tourism. Concurrently, the outlook of integrating a hydrogen energy storage system is evaluated in terms of autonomy and minimisation of the port's GHG emissions; the outcomes can be easily compared to the other examined ESS of the previous step.

The last step is an applied assessment framework to provide insights into the design and the optimal sizing of an energy dispatch strategy to smart control a seaport HRES, ensuring operational stability and safety. The proposed framework provides a sustainable, reliable, cost-effective, and highly replicable solution. The port of Heraklion was selected as the testbed to be presented due to its high energy demand and the sustainable vision of the port's authorities. The port's personnel provided crucial insights on several port operations to properly design and formulate the control algorithms.

After following the steps mentioned above, the nZEP concept is a feasible, reliable and sustainable vision for the future of ports.

5.1. Renovating the port's outdoor lighting by implementing a SOLCS

5.1.1 Case study's detailed description

The case study is the Port of Rethymno, a small-sized Mediterranean port, which is of great importance due to its strategic position (Figure 5.1), operating weekly routes with the port of Piraeus. It mainly serves domestic ships, transporting thousands of tourists yearly, impacting the island's economy. Rethymno port was picked as the ideal case because of the extreme energy consumption of the known outdoor lighting infrastructures. This port can be a paradigm for other numerous small ports worldwide was an essential feature for the decision process; there is high replicability of the suggested method after modifying the input data because there are thousands of similar seaports worldwide with similar outdoor lighting issues.

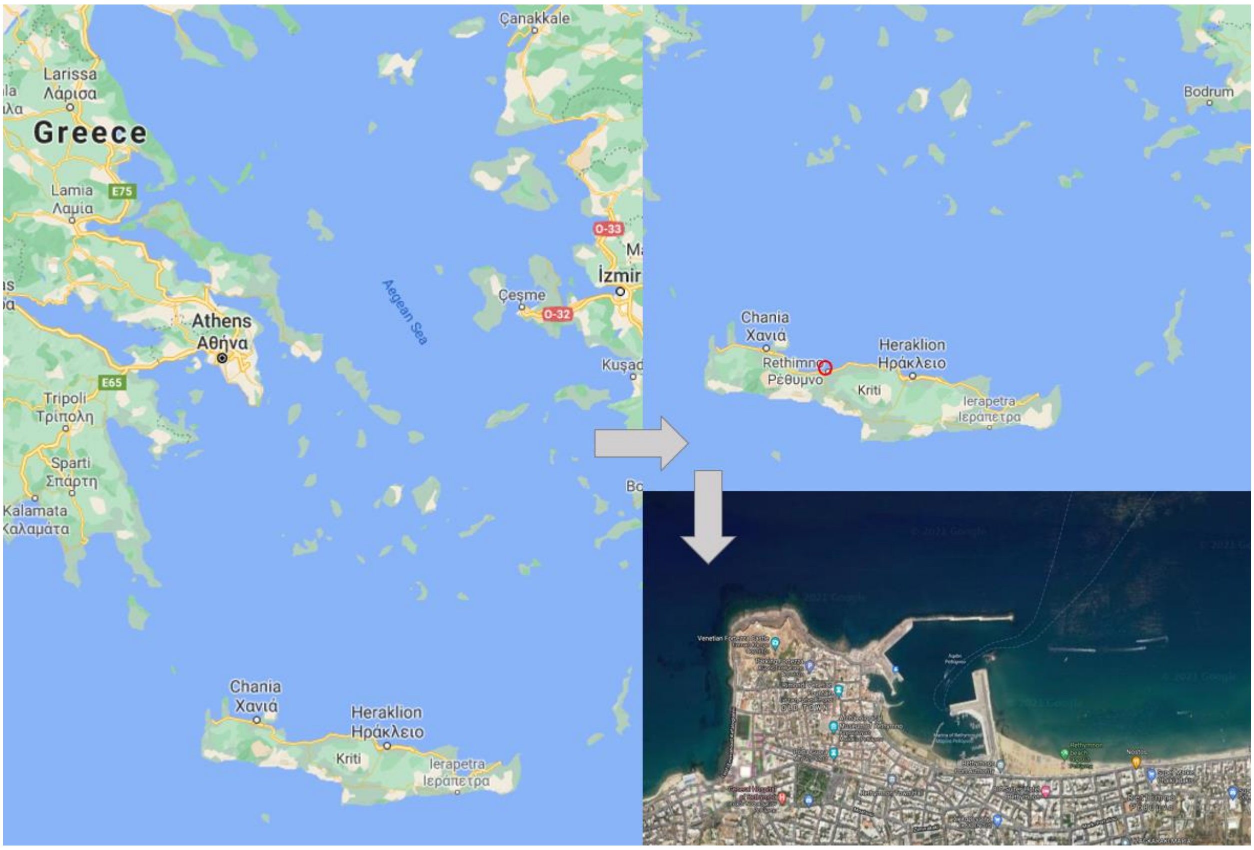


Figure 5.1. The geographical location of the Rethymno port

The actual energy demand data's acquisition and utilisation are among the crucial innovations of this research study compared to most past studies, let alone the collaboration with the port's personnel to install the smart metering systems.

Specifically, the research team acquired and used actual data regarding every aspect of the research study, such as the total port's hourly energy demand, the energy cost, and the proposed technologies' regional pricing.

Seaports' energy demand is dynamic due to their complex operations; the various subsystems and the uncertain factors (weather conditions, tourism) strongly affect the energy consumption, establishing a stochastic nature that can be barely predicted. The stochastic aspect is handled and eliminated by utilising the 5-year average of 15-min port's energy demand data. The actual 5-year average port's demand profile was analysed, modelled, and integrated into the HOMER tool. An extra 30% of energy was integrated into each timestep data to increase the results' reliability, including the commercial port's energy demand; there are only monthly data available regarding this port's part.

The port's actual energy demand data were acquired by installing smart metering systems in the port infrastructures in collaboration with the port's personnel, enabling the acquisition of a 5-year hourly energy-demand time-series; the energy demand data include all the port operations that use electricity (lighting, vessels, buildings, etc.). The average fixed energy cost is modelled and integrated into the software by studying the monthly electricity bills for the past five years. The communication with the Harbour Management Organisation of Prefecture of Chania contributed to the formulation of the final 35 examined scenarios.

The average hourly energy consumption is usually between 50 to 200kWh (Figure 5.2). Unexpectedly, the daily profile showed that the energy demand is higher during the winter and the high tourism periods (July-August). The port's average annual demand is 705,753kWh, which equals 1933.57 kWh/d, while the peak energy demand equals 182.49kW. The port is energy-supplied explicitly by the island's electricity grid; there are no in-situ RES to contribute to the port's energy demands.

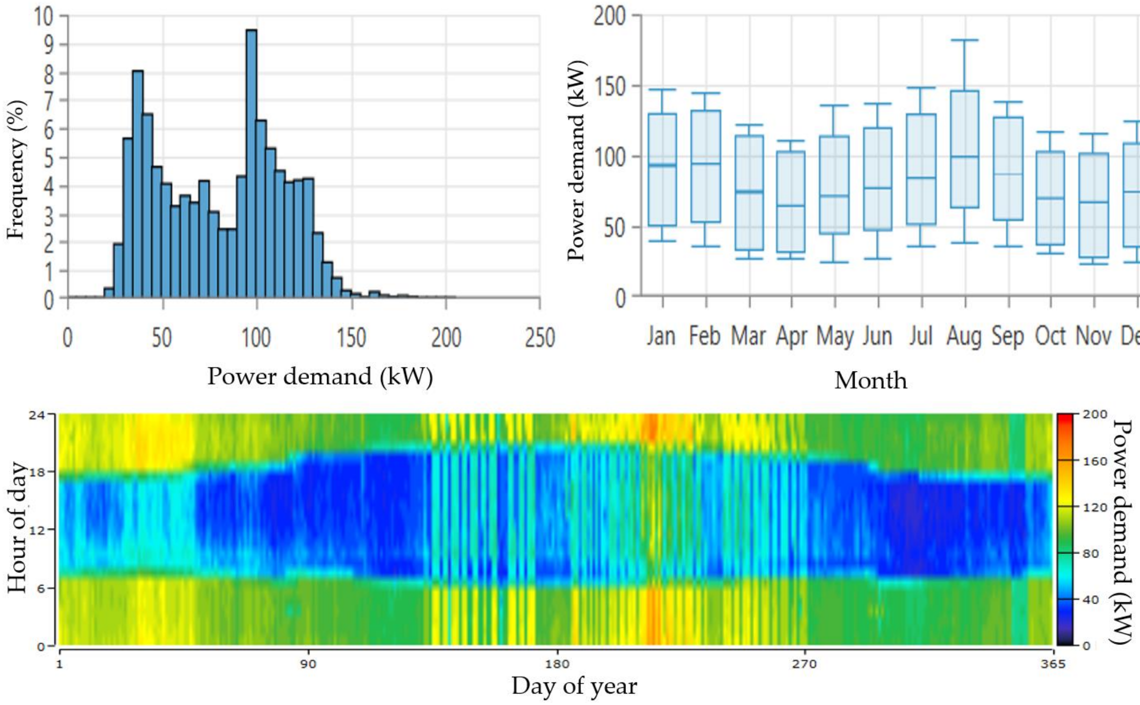


Figure 5.2. Rethymno's port hourly and monthly energy consumption

The renewable resources' availability significantly impacts the HRES efficiency. Figure 5.3 shows the low frequency of extreme wind speed events (histogram) and the mean daily wind speed's fluctuation; the average wind speed is 5.98m/s. PV production is proportionate to the solar radiation and the sky clearness index; their monthly values are presented in Figure 5.4. The average daily solar radiation is 5.28kWh/m^{2}day, indicating the high solar availability in the port's surrounding area.

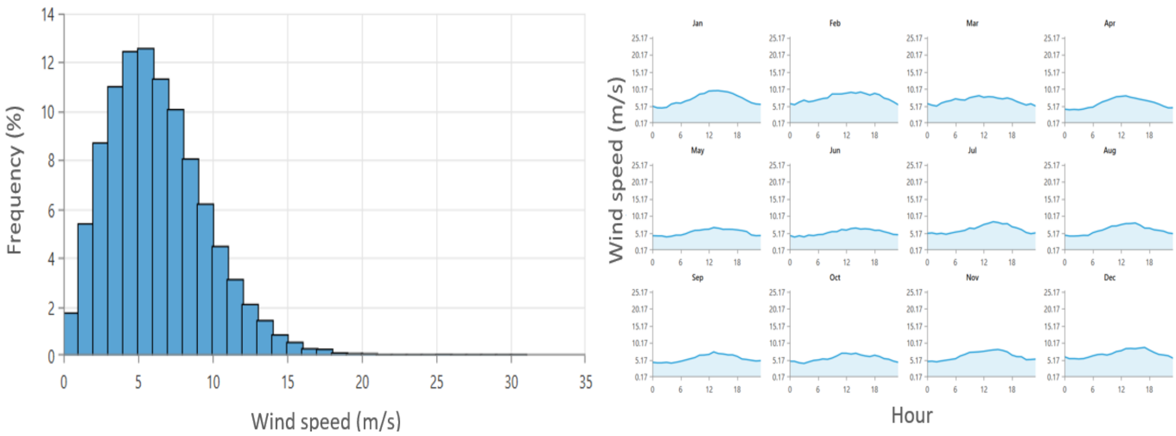


Figure 5.3. Histogram of mean hourly wind speed and area chart of the mean daily wind speed

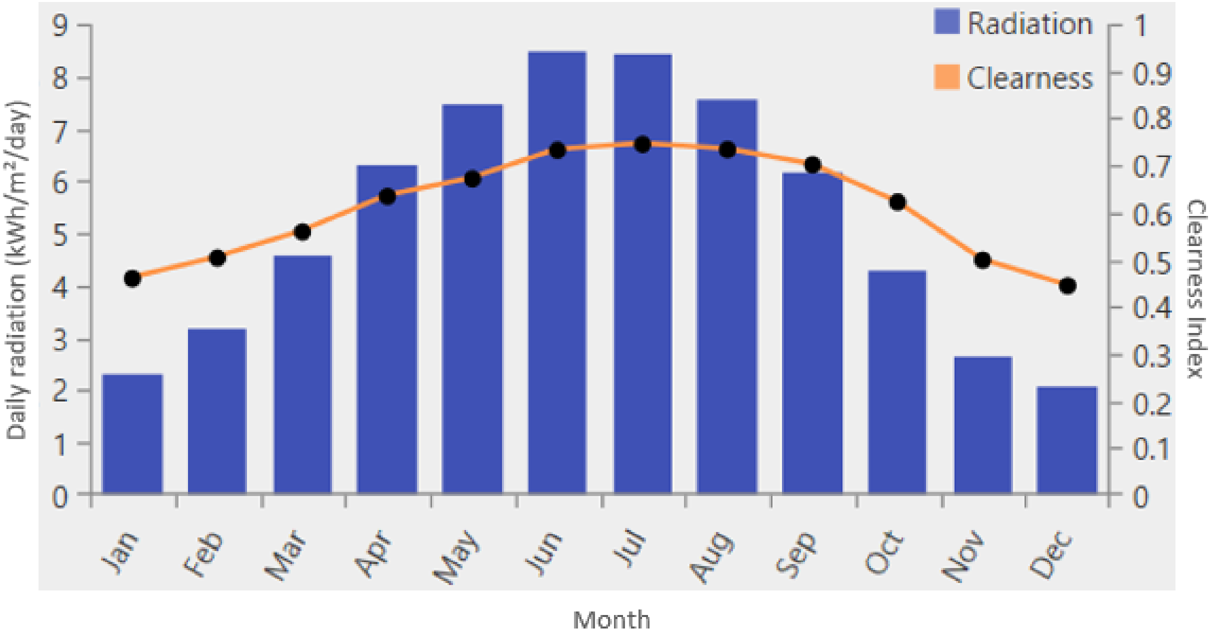


Figure 5.4. Mean monthly solar radiation and clearness index of the port's area

5.1.2 Smart Outdoor Lighting Control System Methodology

5.1.2.1 Proposed SOLCS main stages

The applied methodology is structured following three main stages):

(a) the total renovation of the existing obsolete lighting equipment;

(b) the daylight-harvesting technique -modified for outdoor spaces-, which is the 2^{nd} stage, and

(c) the smart occupancy lighting control strategy for each space.

A SOLCS is developed and explained in stages (b) and (c). Its most attractive asset and main originality is its replicability, while it can be applied in any case, either indoor or outdoor, just by making various required modifications. A prerequisite for providing reliable and efficient outcomes is the input of the appropriate data for the lighting infrastructures and the outdoor/indoor spaces' illuminance regulation standards.

Greece is a naval-related country that incorporates a high potential for sustainable ports. According to an existing research topology, one hundred twenty-eight ports are located in Greece, out of which four are International, ten are National, and the rest 114 are local ones, according to an existing research topology [196,361]. The medium-sized Mediterranean port of Rethymno (Crete, Greece) is selected as the most favourable testbed for this study due to its high energy saving potential; the actual data were obtained in collaboration with the port authorities and personnel visiting and reviewing the current lighting infrastructures. The majority of the outdoor luminaires are equipped with low energy-efficient compact fluorescent lamps. Today, the lighting outcome is insufficient, in terms of uniformity, according to the latest EU regulation due to economic reasons. The port is divided into 21 subspaces that serve different operations (Table A.1.); primarily, the EU illumination and uniformity standards are different per subspace. It is mainly operating to (a) serve the needs of a transportation vessel twice a week during summertime, (b) serve the needs of fishing boats and smaller vessels, (c) facilitate two big parking areas with more than 100 parking lots available, and (d) facilitate the maritime authorities' buildings.

The research team divided the port area into subspaces to ensure optimal lighting control per subspace. For instance, the inner part is used only two days per week, which means that the access is strictly restricted for the rest of five days; there is no need to provide that much illuminance as the legislative values indicate.

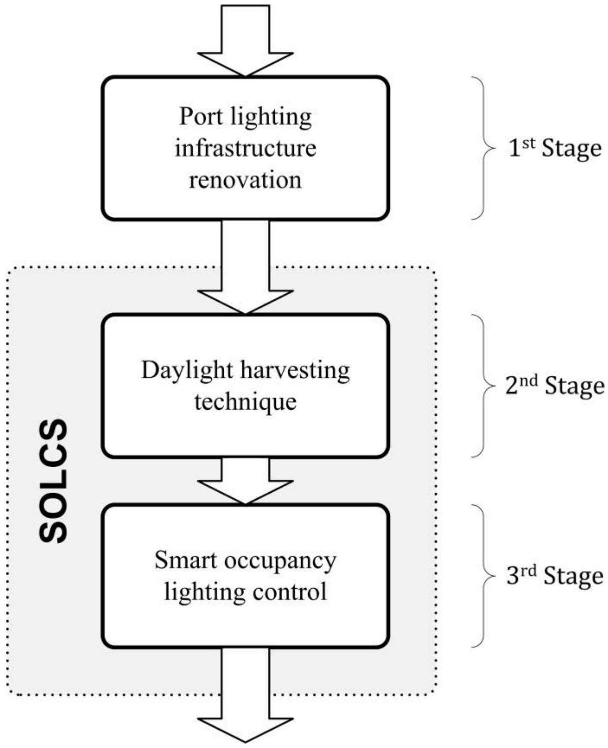


Figure 5.5. General flowchart of the proposed methodology

5.1.2.2 Total port's lighting infrastructure renovation – 1st stage

First, the existing lighting infrastructures are simulated and evaluated using DIALux; the existing luminaires and their location proved not optimal. Thus, the lighting infrastructures were redesigned, incorporating a new, contemporary lighting system following the most recent EU legislation, concurrently guaranteeing end-users safety and comfort (Figure 5.6). Figure 5.7 presents the flowchart of this stage.

DIALux, commonly used in lighting applications, ensured that the lighting model's outcomes would be as accurate and reliable as possible for the baseline and the optimised scenarios. The baseline scenario's simulations were validated by measuring the actual illuminance in the port areas and comparing it with the simulated model's outcomes; the illuminance deviations were less than 5%.

The selection of the new poles and luminaires is based on specific inclusion and exclusion criteria; the poles should be resistant to extreme conditions, the increased salinity on the air particles, and high wind gusts. Also, the luminaires should be capable of being dimmed. The luminaires incorporate the Digital Addressable Lighting Interface (DALI), an industry-standard universal protocol, specified in the International Electrotechnical Commission (IEC) 62386, industrialised for digital, bi-directional communication among all the components of a lighting control system. The comparison of the results of the two scenarios is presented in Figure 5.6.

A baseline case is created according to the current lighting routines. The baseline scenario constitutes a reliable benchmark with which the optimised scenario is compared. However, the operational actions are kept constant, were not monitored, and cannot be predicted.

Significant emphasis is placed on investing in upgrading the current lighting equipment. Moreover, due to the type of activities carried out in this area, the EU has established legislative limits on lighting characteristics to be adequate and not to give visual annoyance to the readers and workers **Error! Hyperlink reference not valid.**.

Table 5.1. Legislative outdoor lighting restrictions/limits for port areas

Type of region, task, or activity	E_m	U_0	GR_L	R_a
General lighting of shipyards' premises, prefabricated goods storage areas.	20	0.25	55	40
Short-term management of large units	20	0.25	55	20
Ship's hull cleaning	50	0.25	50	20
Painting and welding of the hull	100	0.4	45	60
Installation of electrical and mechanical components	200	0.5	45	60

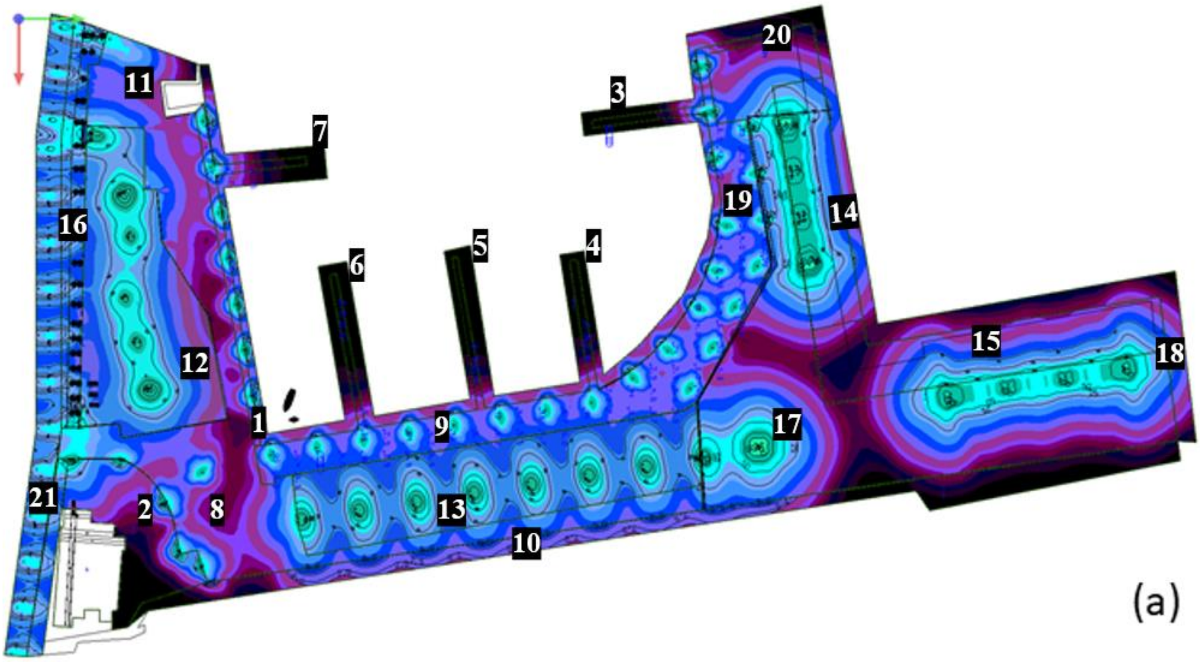
- U_0: Minimum luminance uniformity of each colour.
- E_m: Minimum allowed brightness value
- GR_L: Maximum glow limit from the CIE Glare Rating system
- R_a: Marker that shows the temperature of the lamp's color

A smart control algorithm is created at the second step to substitute the conventional port lighting schedules, which are currently widely applied worldwide. The lighting control's typical schedule is based on a simple time-based power on/off strategy; the administration preschedules the luminaires' operation. Daylight is not considered a fact that may lead to energy savings; the luminaires are powered on, neglecting daylight during operation hours and operating at full load.

This research attempts to take advantage of the usable daylight amount by dimming the luminaires' output power to provide the required different illuminance. Precisely, the sun's illuminance during the day-hours is calculated by multiplying the solar irradiance with the appropriate empirical factor. The current sun irradiance data are acquired employing an existing sensor in Rethymno and are indicative for the whole town. Furthermore, the data are validated by comparing them with NASA's Prediction of Worldwide Energy Resources (POWER) and the ones from the National Observatory of Athens [362].

At the third stage, an occupancy-based control system is proposed to enhance the SOLCS's efficiency further. At the moment, each subspace's occupancy is disregarded, leading to noteworthy energy wastes for spaces that are not used during night hours. This research proposes a lighting control algorithm incorporating the subspaces' occupational data. The information about each subspace's occupancy is acquired by asking the port administration and staff relevant questions. An empirical per quarter-hour time-series of the occupancy (%) was then created using MATLAB; unexpected events were also considered by implementing a random number generation algorithm.

Although some studies have involved the daylight harvesting technique, there is no research combining it with the occupancy control system to provide a complete smart solution. Both algorithms of stages 2 and 3 aim to optimise the lighting output of the luminaires, ensuring that all subspaces are appropriately illuminated, both regarding the illuminance (lux) and the uniformity (U_o). When the U_o levels are satisfied, it is assumed that the user's satisfaction and safety are enhanced. Most of the available studies for outdoor spaces consider the subspaces' illuminance levels neglecting the daylight illuminance, indicating the innovation and the importance of this research study.



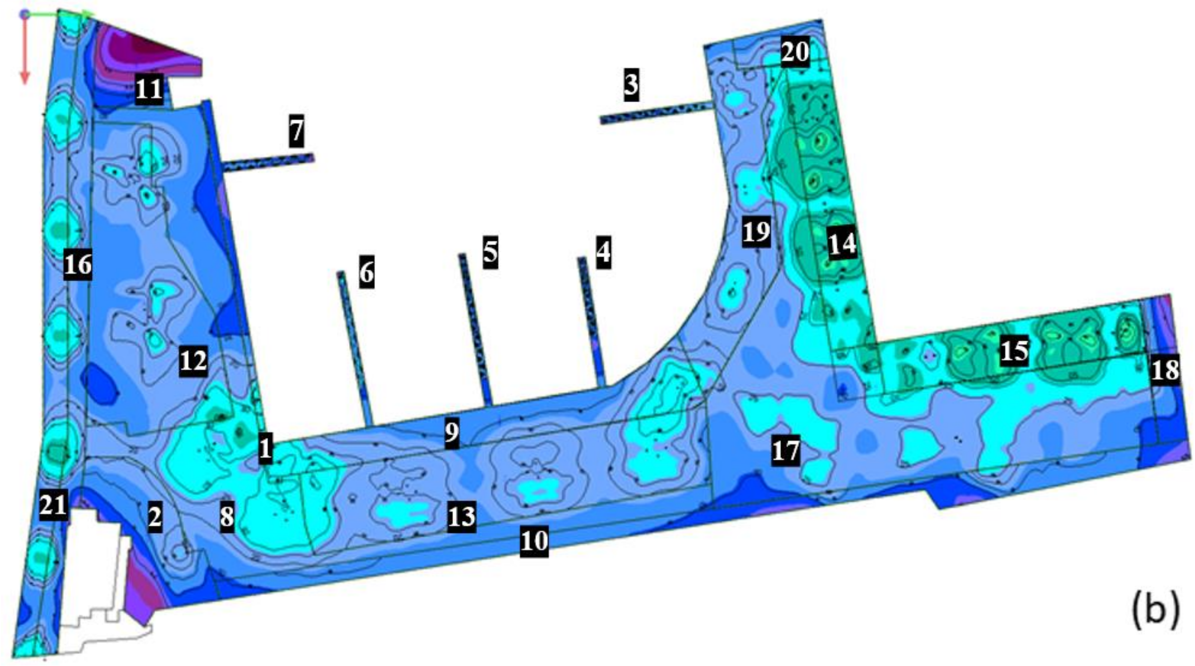


Figure 5.6. Comparison of the port's subspaces' illuminance (top view) for the baseline (a) and the proposed case (b)

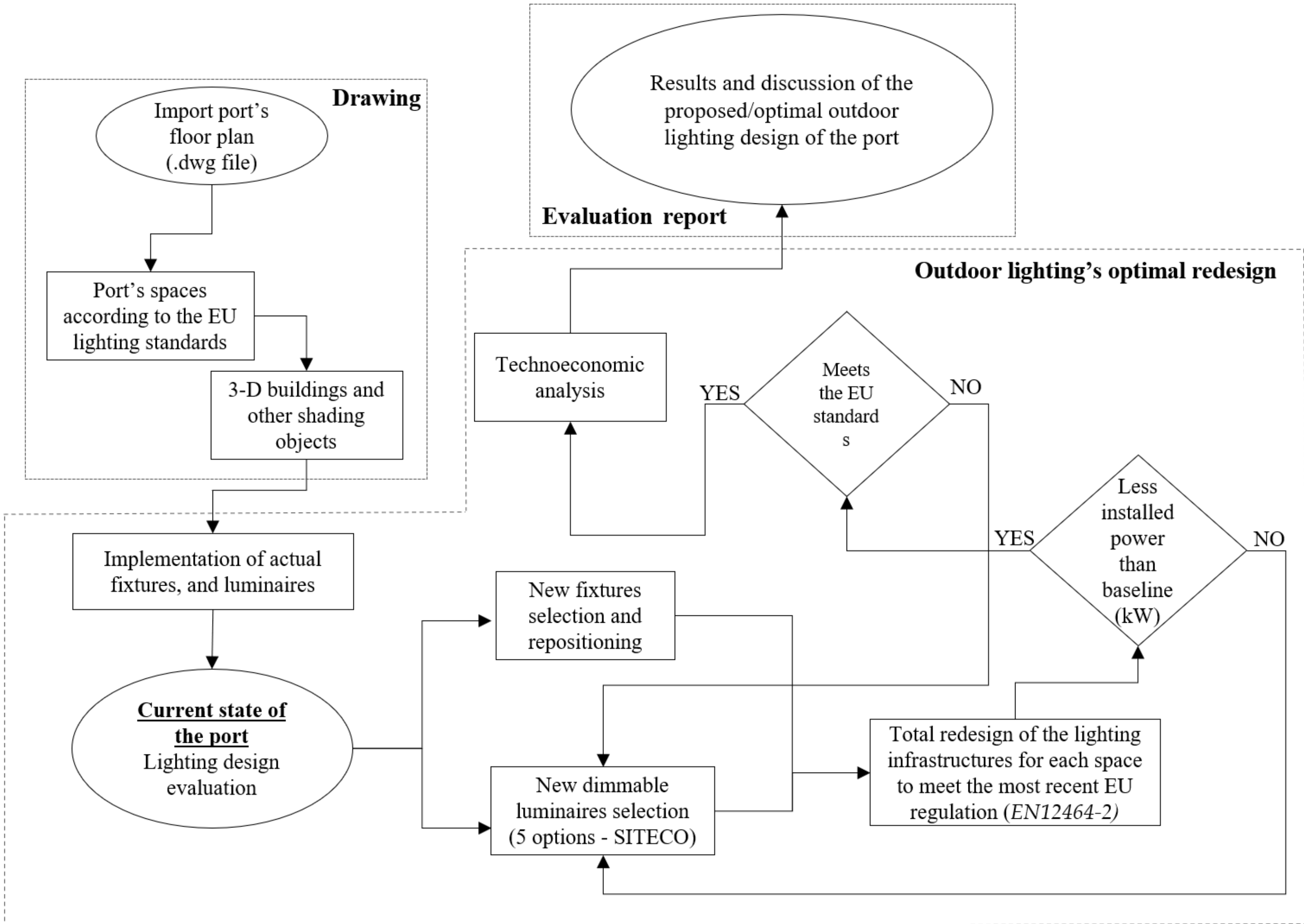


Figure 5.7. The 1st stage of the adopted methodology; the marina's lighting equipment total renovation

5.1.2.3 Control algorithm 1 – Daylight Harvesting – 2nd stage

The daylight harvesting technique takes advantage of ambient sunlight as a natural lighting source. The present research work takes advantage of (a) the per quarter-hour random data and (b) the actual hourly data for the town of Rethymno due to the lack of installed sensors in-situ. The port area's illuminance data is created using a developed algorithm involving actual hourly data for Rethymno and random distribution. The sunrise and sunset time of the day are set according to their empirical daily values for Rethymno. The illuminance measured values are modified by a smart sub-procedure created by the research team, developing an hourly illuminance time series.

An assumption has been made for the actual illuminance data; the actual illuminance at the sensor's location is supposed to be the same as the hypothetical one at all the port subspaces. Since the obtained illuminance data are hourly, a new algorithm was created to convert this data to a per quarter-hour basis. To calculate the per quarter-hour fluctuation of the illuminance during the day, a smart procedure was developed considering the daylight's illuminance. According to this procedure, the first and last hour per day are identified when sunrise and sunset occur. The differences between the per quarter-hour illuminance values in these hours' intervals are higher than those during the midday hours. This procedure handles all these differences, extracting from the hourly data a time series of 15-min interval data involving randomness and ensuring that the newly-created time series is realistic and accurate.

Mathematical models quantify the impact of daylight's illuminance on the actual illuminance demand for outdoor subspaces. Thus, the actual value of incident lux is calculated according to the geometry and the light's desired uniformity, exploiting the DIALux's outcomes, ensuring reliable and solid results. At the next step, the actual sun illuminance is being subtracted from the total lux demand per subspace (Figure 5.8); the difference is the lux demand from the artificial light sources, supplementary to the available lux value from the sunlight, indicating the real lighting needs per subspace during each timestep.

Subsequently, the SOLCS searches for the minimum actual dimming wattage per subspace's available luminaires that could provide the required illuminance. Each luminaire's contribution is calculated from the DIALux outcomes to eliminate any possible fluctuation of subspace's lighting uniformity. Lastly, the subspace's per quarter-hour energy demand is estimated according to each timestep calculated lux demand. Consequently, the first decision variable of the system is the ambient sunlight's illuminance.

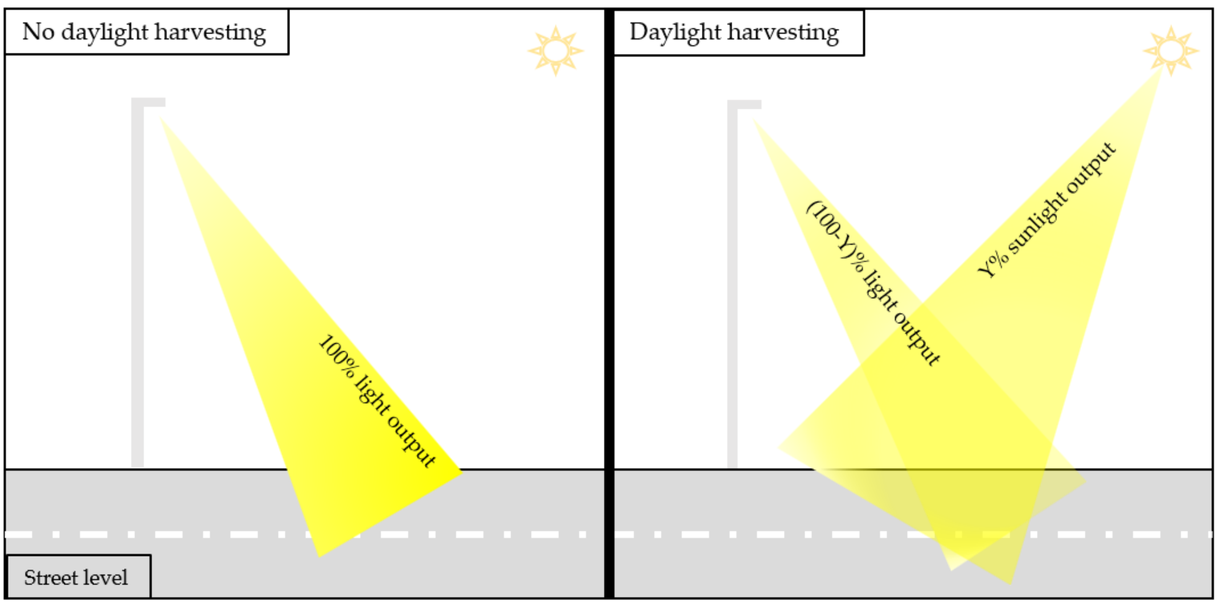


Figure 5.8. Daylight harvesting technique for the hour before the sunrise and the sunset

The actual energy demand per timestep is calculated by using equation 20.

$$E_{SLDS} = \sum_{i=1}^{i=5} \sum_{j=1}^{j=35040} \sum_{k=1}^{k=21} W_{rmin} \quad (20)$$

E_{SLDS} = *the total energy needed for the smart lux dimming system*

$W_{r\min}$ = *the least available dimming wattage of each lamp capable of providing the required lumens*

5.1.2.4 Control algorithm 2 – Occupational Dimming – 3rd stage

The occupational dimming algorithm considers every subspace's occupancy for the non-operation hours to properly dim the luminaires' power level. Specifically, an algorithm that calculates the occupancy (%) per subspace is created based on the acquired information from the port's personnel. Expressly, the staff indicated specific lower and upper practical limits of each subspace's occupancy for the different periods of the day. Indicatively, during the operating hours (06:00-18:00), the per quarter-hour occupancy (in the span 0-10) is considered as 10 (100%); during the night hours right after the operation hours (till 00.00), the per quarter-hour occupancy is between 3 and 10, while after 00.00 the per quarter-hour occupancy is between 0 to 6.

The occupancy factors are calculated using a properly developed algorithm, picking random values between the lower and upper limits. The random number generator ensures that the outcomes are not biased. Three specific high energy-consuming subspaces serve passengers; thus, they are not operating during night hours as the access is restricted. The research team decided not to power off the subspaces' lighting but set lower boundaries for safety reasons.

This control algorithm's concept is that even if no person is at the port subspaces, the luminaires will never be dimmed below 40% of their rated power, ensuring adequate illuminance during all night-hours (Figure 5.9). The energy savings when the lights are turned off compared to the suggested dimming are not that much. Thus, the research team adopted this condition. The total energy demand from the implementation of this technique is calculated by equation 21.

$$E_{oc} = \sum_{i=1}^{i=5} \sum_{j=1}^{j=35040} \sum_{k=1}^{k=21} [(0.6 \times E \times OcF) + (O.4 \times E)] \quad (21)$$

E_{OC} = the per quarter-hour energy demand from the implementation of the occupational dimming algorithm

E = the per quarter-hour energy demand

OcF = the occupation factors

This technique can be used alongside the daylight mentioned above harvesting technique, converting equation 21 to equation 22.

$$E_{oc} = \sum_{i=1}^{i=5} \sum_{j=1}^{j=35040} \sum_{k=1}^{k=21} [(0.6 \times E_{SLDS} \times OcF) + (0.4 \times E_{SLDS})] \quad (22)$$

E_{OC} = *the per quarter – hour energy demand from the implementation of the occupational dimming algorithm*

E_{SLDS} = *the total energy needed for the smart lux dimming system*

OcF = *the occupation factors*

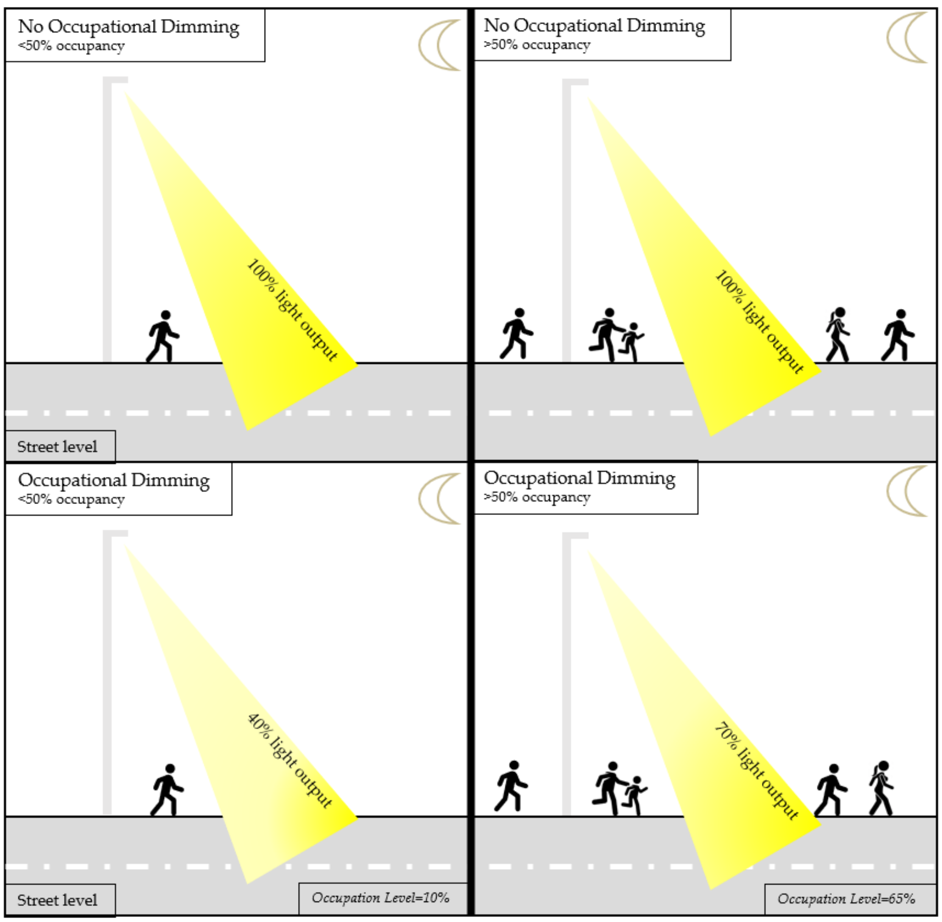


Figure 5.9. Occupational Dimming technique for the night hours.

This technique can also be interpreted for indoor cases, incorporating high scalability and applicability.

5.1.2.5 Control algorithm 3 – Combination of 2nd and 3rd stage

The optimal results can be achieved by combining the control algorithms as mentioned earlier and their subscripts to create a complete SOLCS, providing the most effective solution after several steps.

The first step is to provide the required input data through four different ".csv" type data files. These files include the data needed for (a) the hourly daylight, (b) the per quarter-hour operation and occupation factors, (c) the unique characteristics of each subspace, and (d) the specifications of the suggested DALI luminaires. The hourly daylight data is converted to per quarter-hour, applying a smart algorithm, explicitly described above, created by the research team. Next, the smart system checks the operation factors and sets the per quarter-hour energy demand to the baseline case. The next step is to investigate the ambient daylight illuminance and each subspace's actual lux demand. The actual illuminance per subspace is calculated using DIALux, considering its geometry and unique characteristics. In most cases, the required illuminance is higher than the legislative limits due to the complex geometry and the subspaces' shadings. Then, the optimal wattage of each luminaire (local minimum) is set by the smart algorithm; if there is more than one type of luminaire in the same subspace, the actual proportion of their lumens output is taken into account to avoid possible losses and interruptions on light uniformity.

The last step of this methodology is the human presence's calculation in each subspace and the appropriate luminaires dimming level, based on the predefined values; the lowest possible value is 40% of the rated power, ensuring that even in cases that nobody is at the port subspaces, they will be adequately illuminated for unexpected events. To summarise, this SOLCS is universal and highly replicable; it can be used either for indoor and outdoor cases by adjusting the specified parameters. Its overall operation is presented in Figure 5.10.

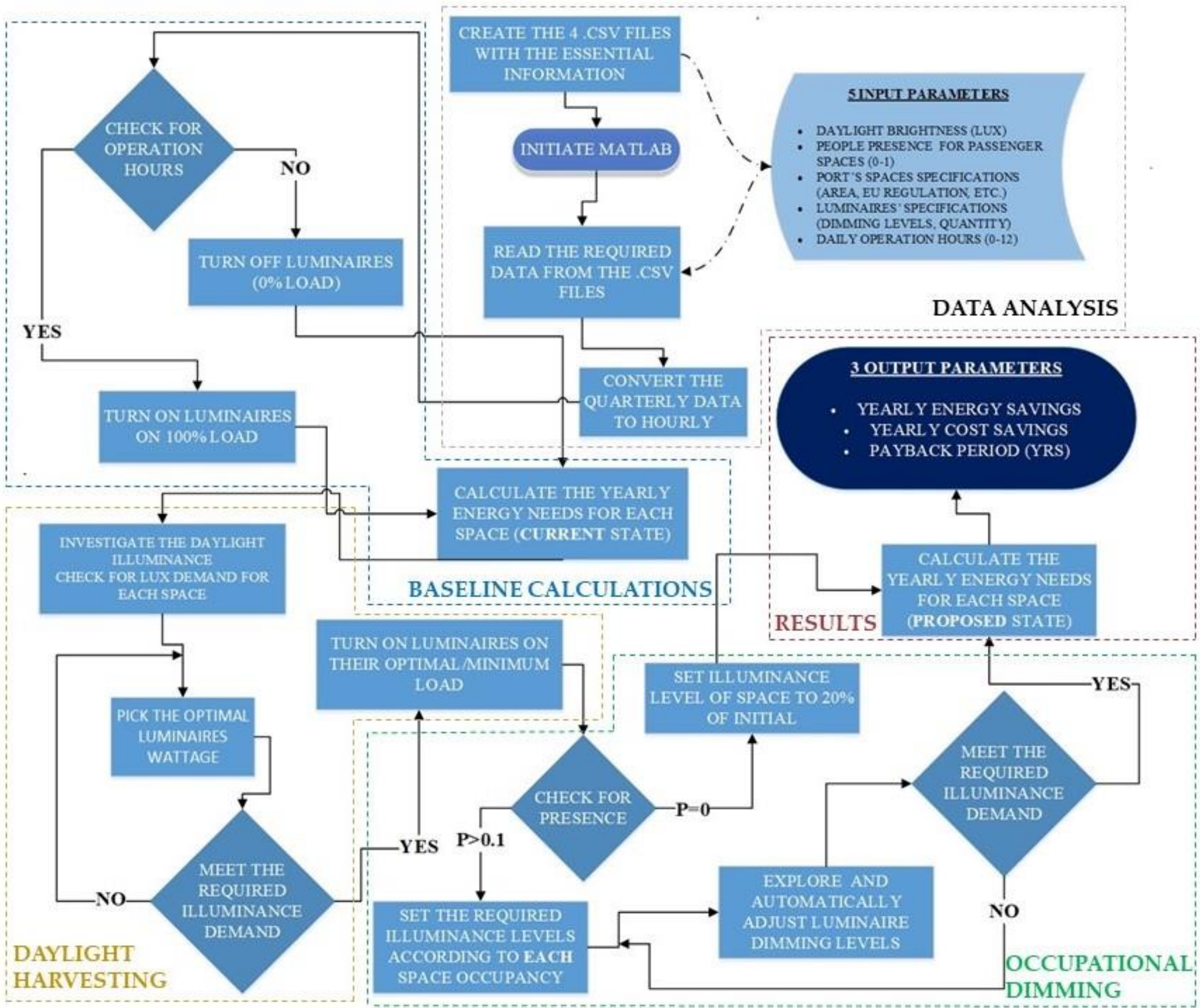


Figure 5.10. Flowchart of the smart outdoor lighting control system

5.1.3 Results of the Smart Outdoor Lighting Control System

The current lighting infrastructures consume more energy (96,190 kWh/yr) than the optimal because of their old-fashioned technology and poor location; thus, the need for replacement and renovation is urgent. As for the 1st stage, the new lighting system is much more effective than the baseline (current) one. Indicatively, the simulation results prove that energy demand is reduced by 21.3%. For this case, the total yearly energy demand is reduced from 96.2 to 76.7 MWh, which corresponds to 15.1 tCO_{2eq}[1] savings. Similar past initiatives have shown that even higher energy savings can be achieved; the possible energy savings are related to the existing luminaires' technology and output power. Figure 5.11 depicts the daily energy and CO_{2eq} savings due to the 1st stage of the methodology.

At the 2nd stage, a smart dimming controller, considering the daylight's illuminance, integrated into the system, controls the luminaires' total power output. According to the most recent EU legislation per subspace, the required luminaires' output is calculated by subtracting the daylight's illuminance from the total required illuminance.

It has been deducted that applying the daylight harvesting technique to indoor subspaces can be beneficial and fruitful; the energy demand can be significantly reduced, leading to substantial CO_{2eq} savings. However, can it be beneficial for outdoor subspaces? This question is answered in this research work; this initiative's outcomes encourage outdoor subspaces' lighting.

A 31.1% energy consumption decrease is achieved, corresponding to a further 13.7% decrease from the 1st stage; The energy consumption is reduced to 50.3 kWh from 76.7 kWh. Figure 5.11 and Figure 5.12 depict the hourly energy decrease attributed to daylight harvesting in four different subspaces during the shortest (21st of December) and

[1] For the $CO_{2,eq}$ calculations, the energy mix of the island of Crete was taken into account. The island's electricity grid is being supplied 21.47% from RES and the rest 78.53% from fossil fuels combustion. The $CO_{2,eq}$ coefficient is equal to 0.989 $kgCO_{2,eq}$/kWh.

the longest (21st of June) day of the year. The dark blue colour line gives the baseline case, the green line is for the 1st stage, and the yellow line is for the 2nd stage. Regarding the 2nd stage procedure, the energy consumption is lower during the first (sunrise) and the last (sunset) day-hours. This is different among the various subspaces because of the legislative standards; streets and subspaces with low illuminance requirements present the most significant percentage decrease.

5.1.3.1 Simulations results

The proper operation is ensured as there is strong fluctuation among the results per day and subspace. There are subspaces for which the 1st stage is much more effective and efficient than the two smart control systems. For instance, in subspace 21, concerning the main street outside the port, the total installed luminaires power is reduced by 1.45kW, resulting in substantial energy savings (more than 70% of the initial energy consumption). This corresponds to 20kWh/day savings; almost 2.2tn$CO_{2,eq}$ can be saved annually. Meanwhile, for the subspaces with higher installed power, the percentage decrease achieved by the 1st stage is lower; the overall reduction is not proportional to this percentage decrease, as it is referred to as higher amounts of power. For instance, regarding subspace 14, where the passenger boarding occurs, the lighting requirements are the highest; an 8.0% decrease is achieved, but this corresponds to 12kWh/day that accounts for 0.74tn$CO_{2,eq}$.

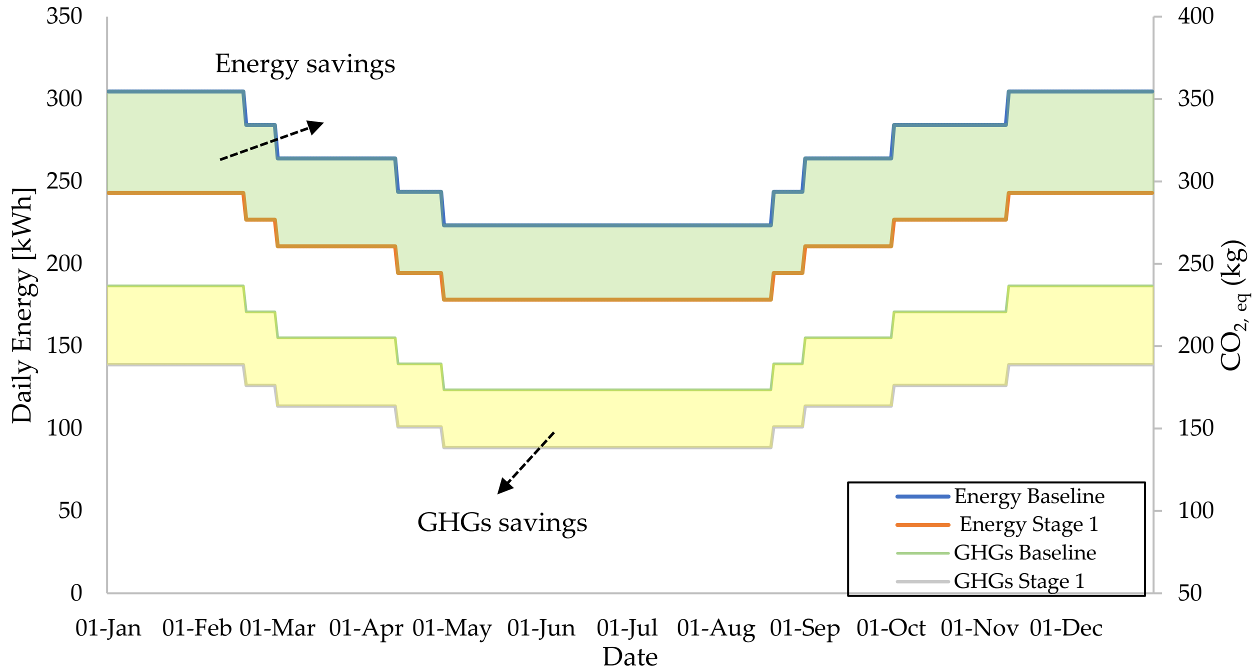


Figure 5.11. Daily energy and GHG savings for the 1st stage of the methodology.

Figure 5.12 illustrates the overall lighting's energy demand on June 21st regarding all stages for (a) the three previously-picked subspaces and (b) the whole port area. This day is the longest of the year; the artificial lighting demands are the lowest. Based on the corresponding figures, the total hourly energy consumption is lower during June than December; the overall energy savings are higher during the winter months because of the higher lighting energy demands.

Similarly, as in December, the total energy savings are considerable for all the methodology stages. The occupancy factors are different for these two specific days, attributed to the visitors' high seasonality on the port's subspaces. Subspaces 12 and 14 present lower energy savings after the 1st stage procedure (replacement and reallocation of the luminaires), attributed to the high legislative illuminance requirements. On the other hand, due to the high currently installed power for lighting, stages 2 and 3 are beneficial, leading to very high energy savings. This methodology takes care of all the possible variations, leading to optimal energy savings.

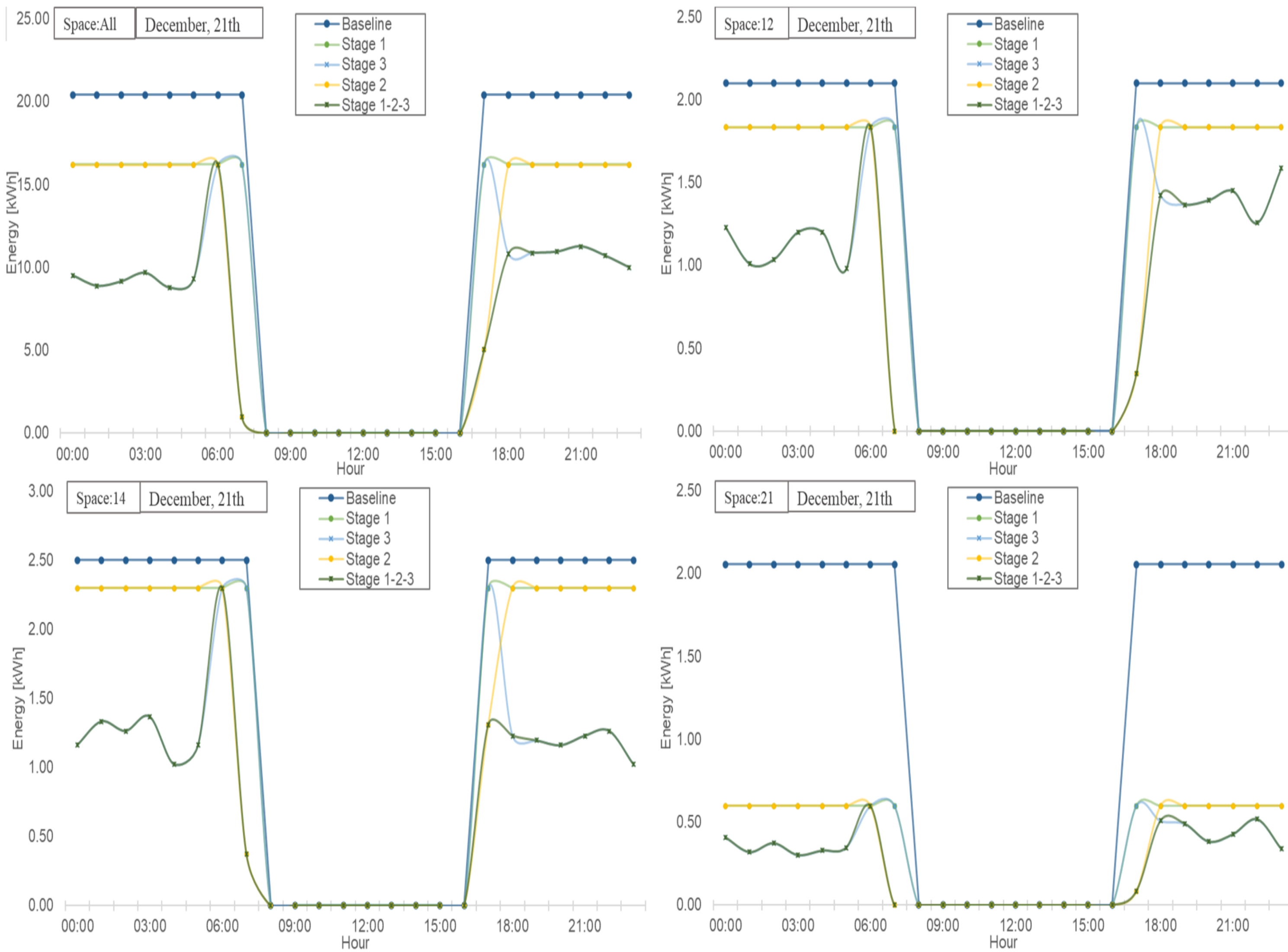


Figure 5.12. Hourly energy demand per stage of the methodology for all four-port subspaces, incorporating different services and operations – Shortest day of the year, 21th December.

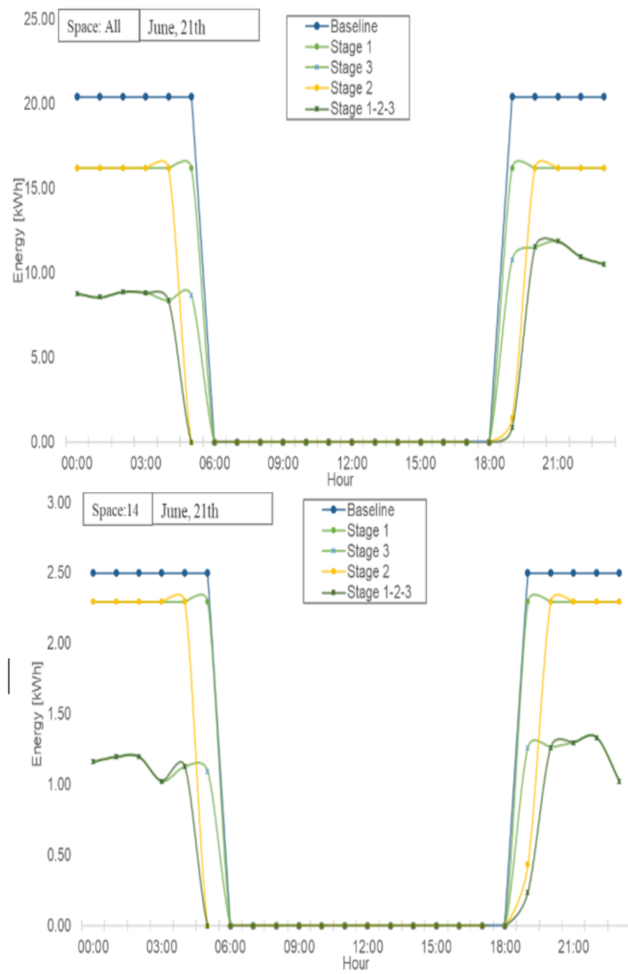


Figure 5.13. Hourly energy demand among the methodology's stages for four port subspaces incorporating different services and operations, for the longest day of the year, 21th June.

Figure 5.14, Figure 5.15, and Figure 5.16 depict the energy savings and the daily illuminance among the methodology's different stages. The energy consumption for the lighting operations of the marina subspaces 12 and 21 are presented, respectively. The energy savings regarding the 1st stage (modification) are satisfactory for the port area and Parking 1 (subspace 12). Additionally, the energy savings on subspace 21 (Venizelou Street) are outstanding for the 1st stage, empowering the proposed system's reliability. On the other side, the more beneficial the 1st stage of the methodology is, the less beneficial the other two stages are than the baseline scenario. This can be easily explained as the total energy savings are higher when the installed lighting power is very high due to the higher energy savings potential. Besides, even if the total energy savings are higher at some stage, the total energy decrease is similar because of the measures' effectiveness. The overall energy savings are remarkable for every subspace when all three stages are implemented. Each stage's drawbacks are counterbalanced by another stage's benefits, resulting in a well-established end-product. Considering subspace 12 (Figure 5.15), where one of the two parking areas is located, the 3rd stage is the most influential; the occupancy factors appeared to be the most effective control strategy. The highest energy consumption reduction for the 1st stage is observed on subspace 21 (Venizelou street). The achievable energy savings are more than 70% (Figure 11). The installed energy decreases to 0.60 kWp; the energy savings potential is reduced dramatically for the following two stages.

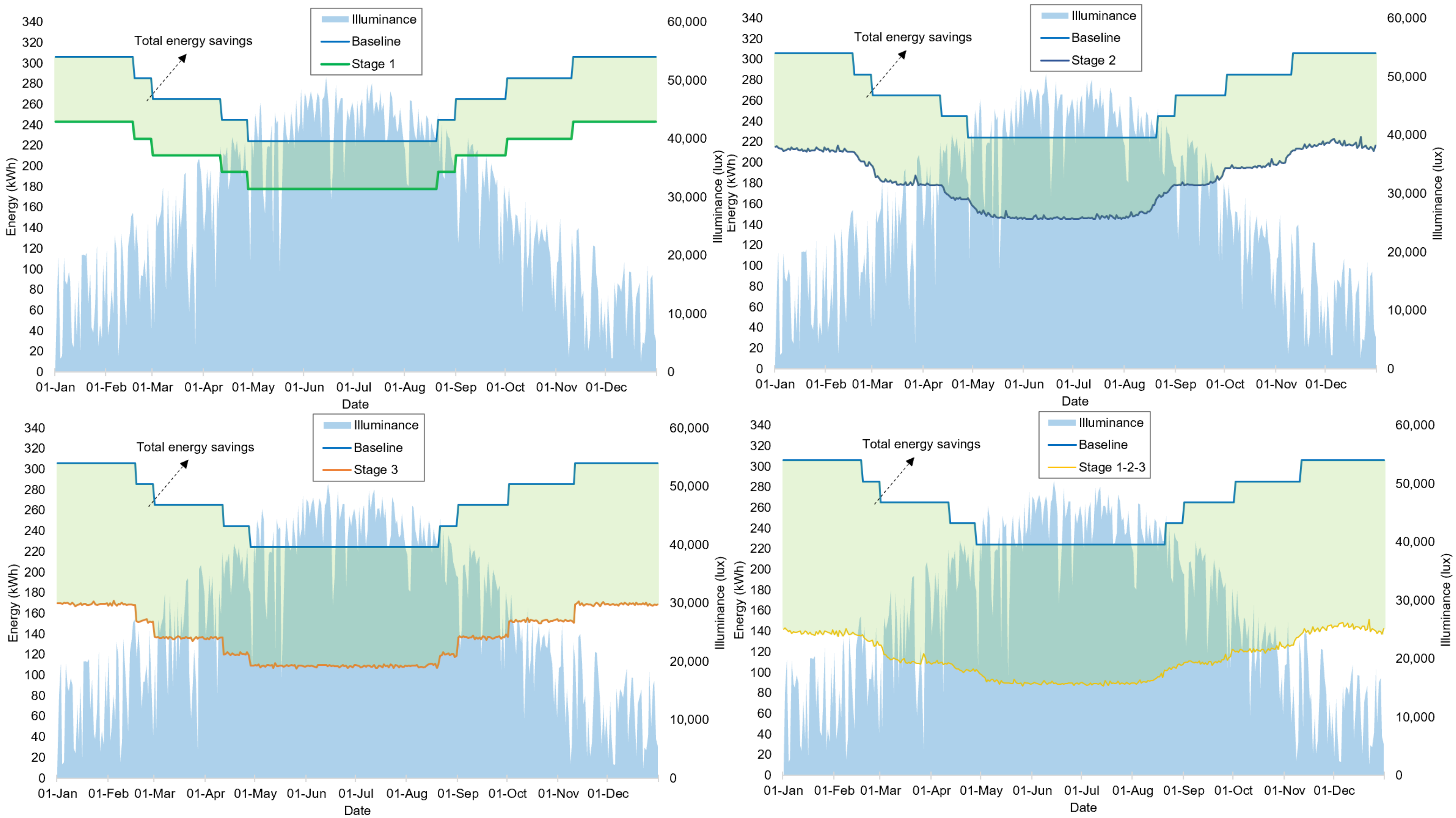


Figure 5.14. Total daily energy demand, daily daylight illuminance, and total daily energy savings for the three stages of the methodology.

5.1.3.2 Discussion of the study's outcomes

Concluding, each stage's high energy savings compensate the low ones of another stage, leading to an overall effective smart solution. Consequently, since the stages are interconnected, the results are optimal, involving all the concepts: (a) renovating the lighting infrastructures, (b) taking advantage of the daylight's illuminance to dim the luminaires' output power accordingly, and (c) utilizing the actual occupancy of each subspace and alter the luminaires' lux output to fit the legislative limits.

Figure 5.17 shows the actual energy consumption's shift from one stage to another. Considering the stages by order, the 1st stage's results (replacing the obsolete luminaires) are substantial. Indicatively, there is a 20.6% decrease in energy consumption compared to the current state. This decrease reaches 31.4% when the 2nd stage is applied, while the total energy savings climb to 56.8% compared to the baseline case. Figure 5.17 also indicates the actual monthly savings due to the implementation of each stage.

If the 3rd stage is compared to the baseline, skipping the 2nd stage, the energy savings are about 48%. This implies that the occupancy control smart algorithm's importance to such situations, due to its high applicability, replicability, and effectiveness alongside its significant low implementation, operation, and maintenance cost.

Also, to further evaluate each stage's effectiveness and efficiency, the total annual energy demands between the consecutive stages are compared. A 20.6% energy decrease from the baseline when applying the 1st stage, a 13.6% decrease between the 1st and the 2nd stage, and a 24.1% decrease from the 2nd to the 3rd stage. The findings, as mentioned above, do enhance the conclusion that the occupancy control system (3rd stage) has the highest potential in such cases.

Lastly, Figure 5.18 depicts the monthly fluctuation of the total energy demand for the whole port. The daylight's illuminance is limited during the winter months. Consequently, the luminaires themselves must provide much more illumination, consuming more energy from the electrical grid.

This SOLCS achieves the highest energy savings during the late-night hours, as expected (Table 5.2). After midnight, there is a restriction to access some port's subspaces; there is energy waste during these hours. By employing the system, this problem is solved, and almost equal amounts of energy are consumed during the early-night hours (before 00:00) and the late-night hours (after 00:00). Indicatively, the energy savings can reach up to 68%, leading to significant GHGs savings.

Although the overall energy savings are significant, the period featuring the highest savings is between May and July due to the more efficient daylight's illuminance. During these months, the sun's illuminance is adequate to illuminate the port's subspaces without needing to turn on the luminaires. The highest amounts of energy are saved during August and November for the post-midnight time zone, while the lowest energy savings characterise these months for the period before midnight. Indicatively, the total energy savings for November are -3.83MWh; the -1.58MWh is for the period before midnight, while the rest -2.25MWh is about the period after midnight. The overall cost of the system is estimated to about 200,000€ due to the high investment cost for replacing the luminaires and their poles.

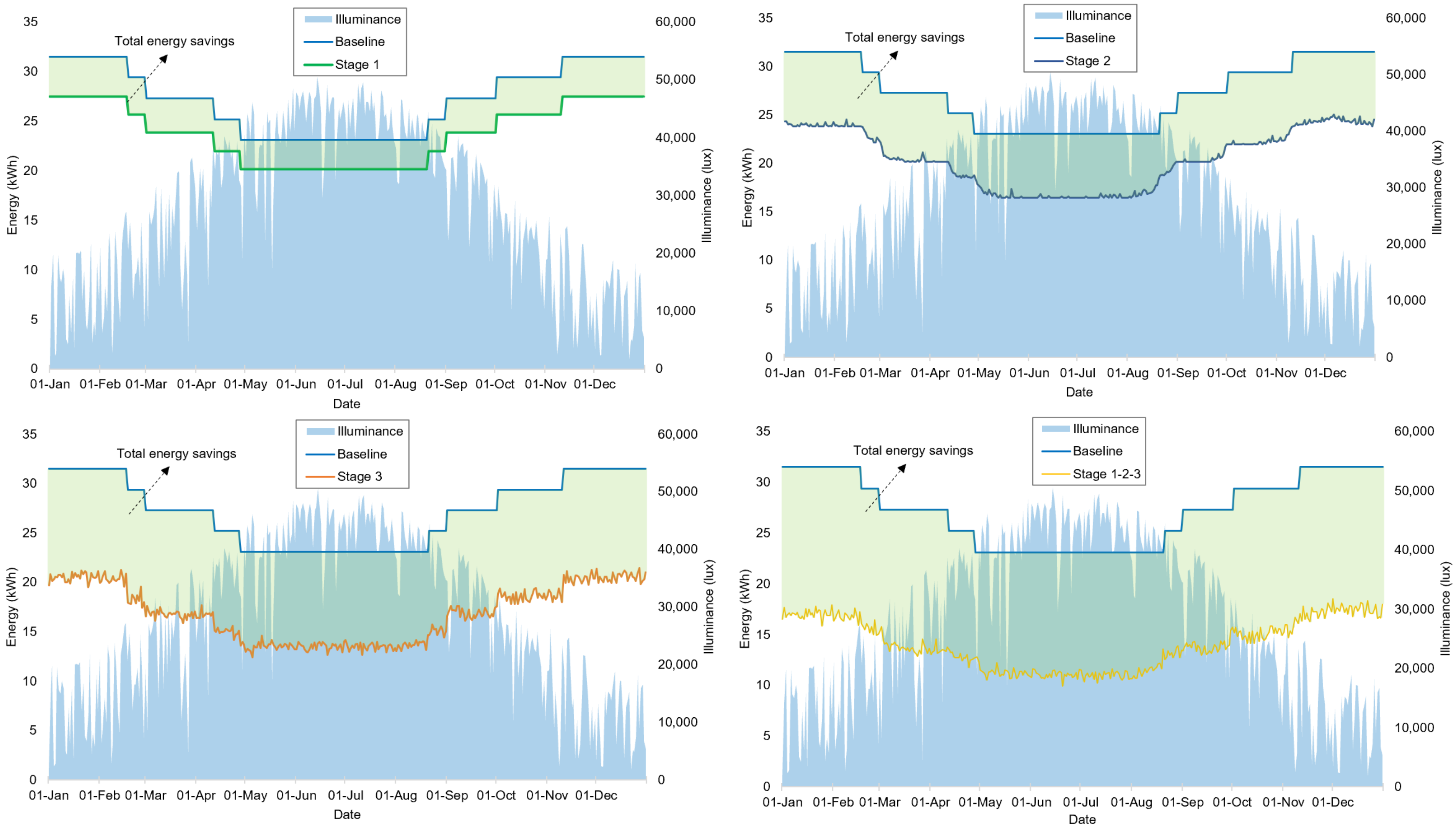


Figure 5.15. Daily energy demand, daily daylight illuminance, and daily energy savings for the three stages of the methodology regarding subspace 12 (Parking area 1)

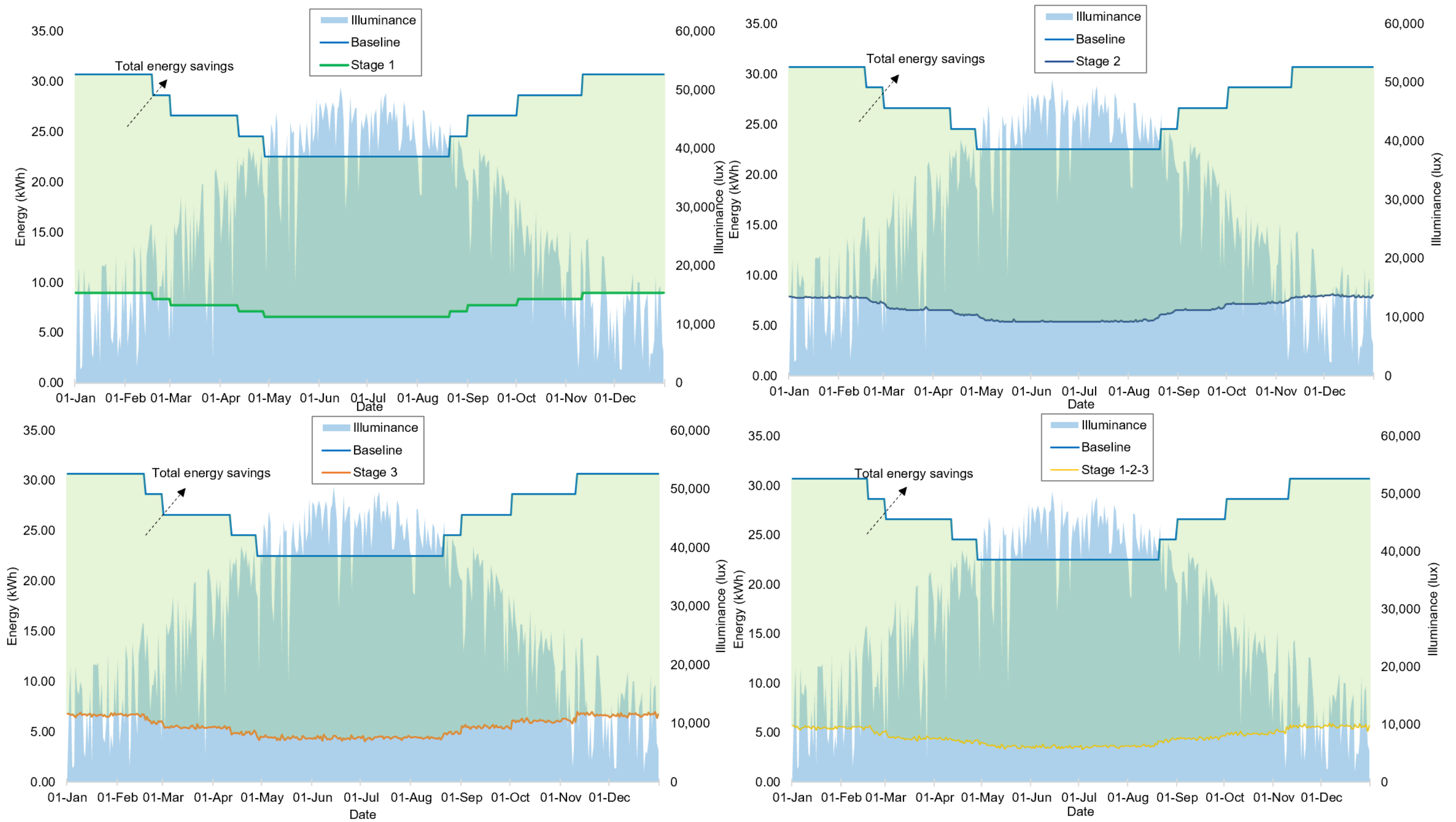


Figure 5.16. Daily energy demand, daily daylight illuminance, and daily energy savings for the three stages of the methodology regarding subspace 21 (Venizelou street)

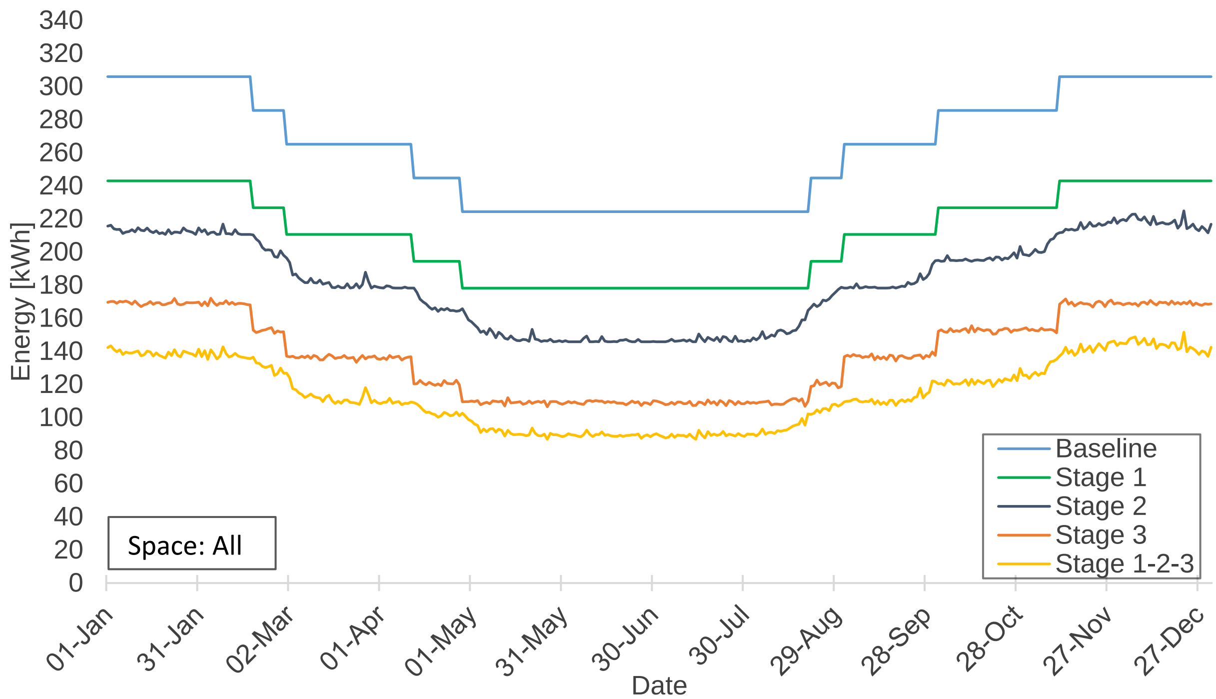


Figure 5.17. Total energy consumption throughout the examined year for the whole port subspace for all three stages of the smart outdoor lighting control system

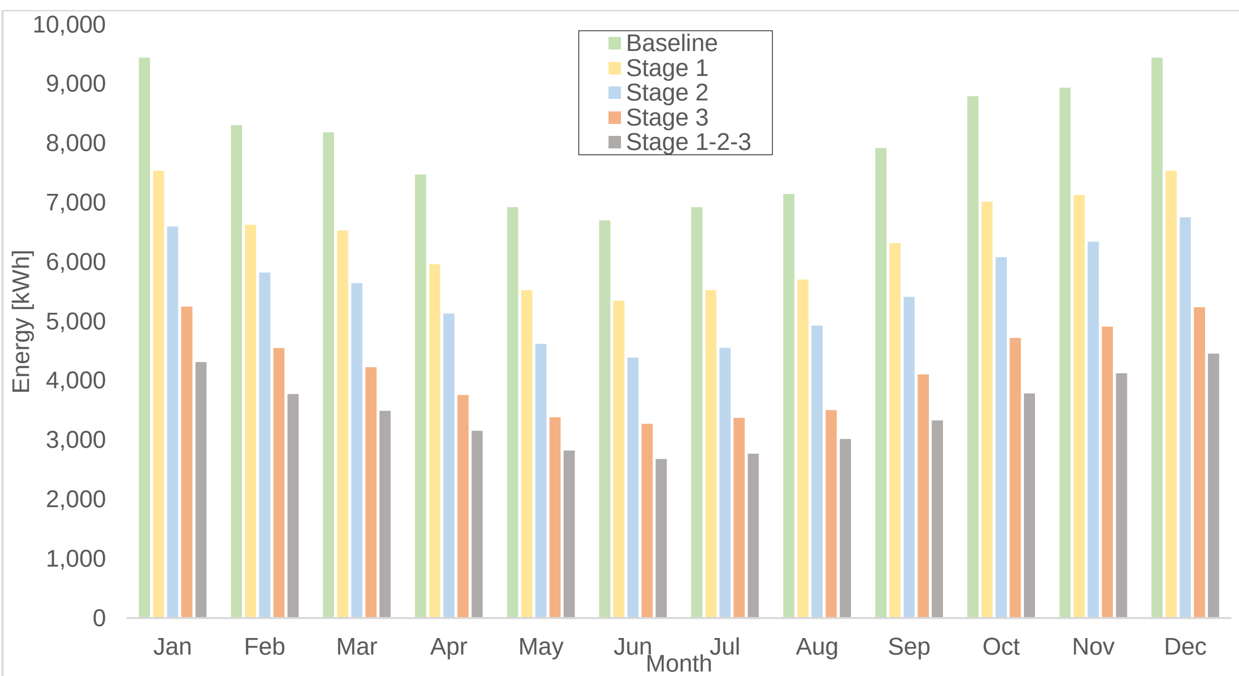


Figure 5.18. Total monthly energy demand for the whole port area for all three stages of the smart outdoor lighting control system

Table 5.2. Energy and GHGs savings for (a) The overall system, (b) the period before 00:00, and (c) the period after 00:00

		All					Before 00:00					After 00:00				
		Baseline[1]	**SOLCS[1]**	**Energy saved[1]**	**% of saved energy**	**CO_2 saved[2]**	**Baseline[1]**	**SOLCS[1]**	**Energy saved[1]**	**% of saved energy**	**CO_2 saved[2]**	**Baseline[1]**	**SOLCS[1]**	**Energy saved[1]**	**% of saved energy**	**CO_2 saved[2]**
Month	**Jan**	9.49	4.31	-5.17	-54.5%	-4.02	4.43	2.09	-2.34	-52.9%	-1.82	5.06	2.23	-2.83	-56%	-2.20
	Feb	8.57	3.77	-4.79	-55.9%	-3.72	4.00	1.80	-2.20	-55.1%	-1.71	4.57	1.98	-2.59	-57%	-2.01
	Mar	8.22	3.49	-4.73	-57.5%	-3.67	3.79	1.72	-2.08	-54.7%	-1.61	4.43	1.77	-2.65	-60%	-2.06
	Apr	7.96	3.16	-4.80	-60.3%	-3.73	3.67	1.65	-2.02	-55.0%	-1.57	4.28	1.50	-2.78	-65%	-2.16
	May	8.22	2.82	-5.40	-65.7%	-4.19	3.79	1.42	-2.38	-62.7%	-1.85	4.43	1.41	-3.02	-68%	-2.35
	Jun	6.73	2.68	-4.05	-60.2%	-3.15	3.06	1.33	-1.73	-56.7%	-1.35	3.67	1.36	-2.32	-63%	-1.80
	Jul	6.96	2.77	-4.19	-60.2%	-3.25	3.16	1.37	-1.80	-56.8%	-1.40	3.79	1.40	-2.39	-63%	-1.86
	Aug	6.96	3.02	-3.94	-56.6%	-3.06	3.16	1.54	-1.62	-51.3%	-1.26	3.79	1.48	-2.32	-61%	-1.80
	Sep	7.96	3.33	-4.63	-58.2%	-3.59	3.67	1.70	-1.98	-53.8%	-1.53	4.28	1.63	-2.65	-62%	-2.06
	Oct	8.22	3.79	-4.44	-54.0%	-3.45	3.79	2.06	-1.74	-45.8%	-1.35	4.43	1.73	-2.7	-61%	-2.10
	Nov	7.96	4.12	-3.83	-48.2%	-2.98	3.67	2.09	-1.58	-43.1%	-1.23	4.28	2.03	-2.25	-53%	-1.75
	Dec	9.49	4.46	-5.03	-53.0%	-3.91	4.43	2.24	-2.19	-49.4%	-1.70	5.06	2.22	-2.84	-56%	-2.21
Total		**96.74**	**41.72**	**-55.00**	**-57.03%**	**-42.72**	**44.62**	**21.01**	**-23.66**	**-53.11%**	**-18.4**	**52.07**	**20.74**	**-31.34**	**-386.01%**	**-24.36**

[1]The total energy is measured in MWh

[2]The GHGs are measured in $tnCO_{2eq}$

5.1.3.3 Typical examples of the 3-D lighting model before and after the implementation of the SOLCS

In this subchapter, six typical examples of the port's outdoor lighting state before and after the implementation of the SOLCS, are presented in the following figures (Figure 5.19, Figure 5.20, Figure 5.21, Figure 5.22, Figure 5.23, Figure 5.24)

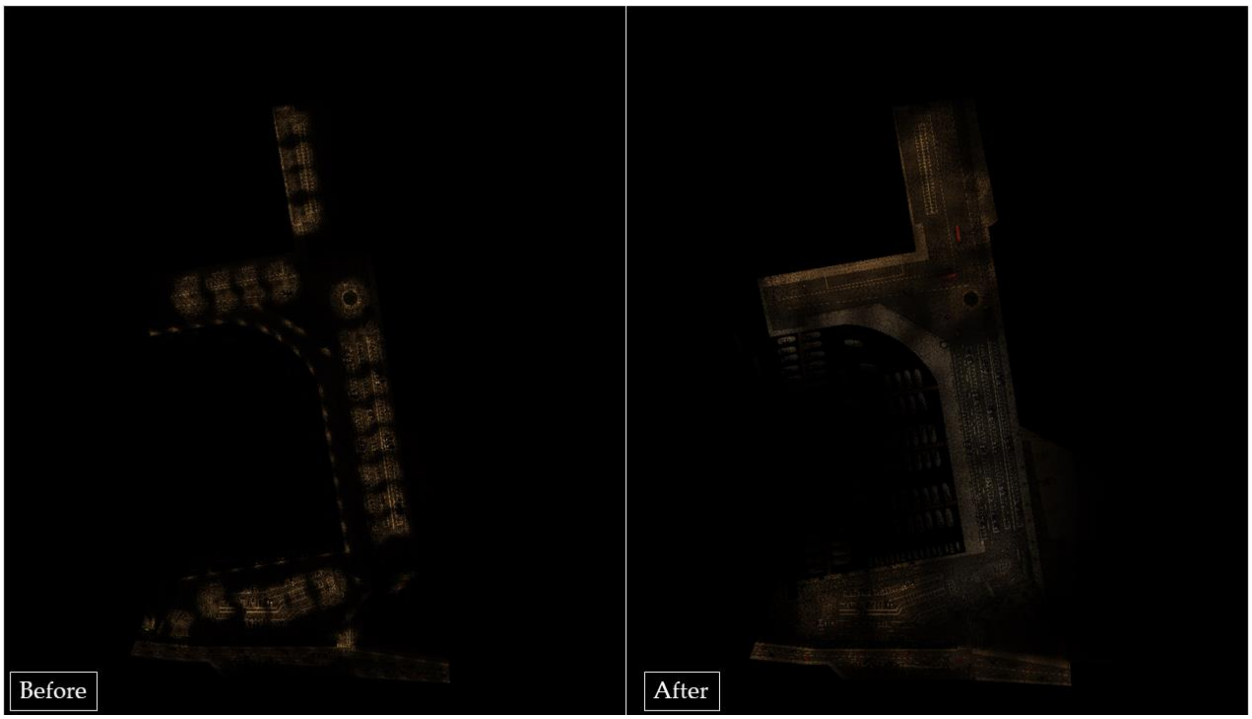


Figure 5.19. 3D depiction of total port's outdoor lighting renovation

Figure 5.20. 3D depiction of inner port's area before and after the outdoor lighting renovation

Figure 5.21. 3D depiction of the port's EV charger area before and after the outdoor lighting renovation

Figure 5.22. 3D depiction of the front view of the port's area before and after the outdoor lighting renovation

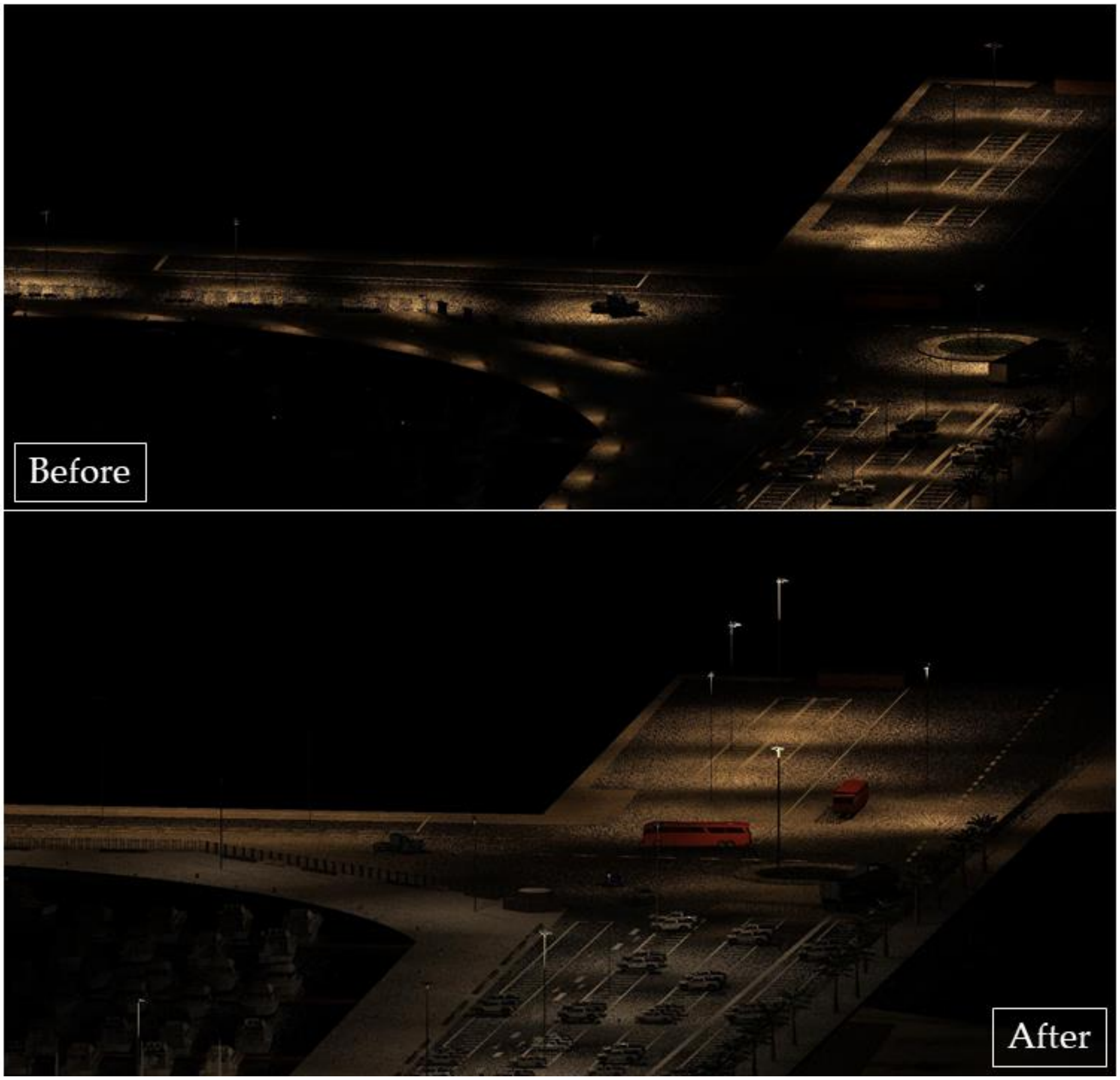


Figure 5.23. 3D depiction of the upper view of the inner port's area before and after the outdoor lighting renovation

Figure 5.24. 3D depiction of the upper right view of the port's area before and after the outdoor lighting renovation

5.2 Optimally sizing a port HRES to cover the energy demand and eliminate GHGs fully

5.2.1 Case study's detailed description

The case study is the Port of Souda, Chania, a medium-sized Mediterranean port (35.49' N latitude and 24.08' E longitude), which is vital due to its strategic position (Figure 5.25) operating daily routes with the port of Piraeus. It mainly serves domestic and foreign ships, transporting thousands of tourists yearly, impacting the island's economy. Souda port was picked as the ideal case because of its high-RES implementation potential. This port can be a paradigm for numerous other ports across the globe was a pivotal aspect for the decision process; there is high applicability of the suggested framework after modifying the input data because there are thousands of similar seaports worldwide.

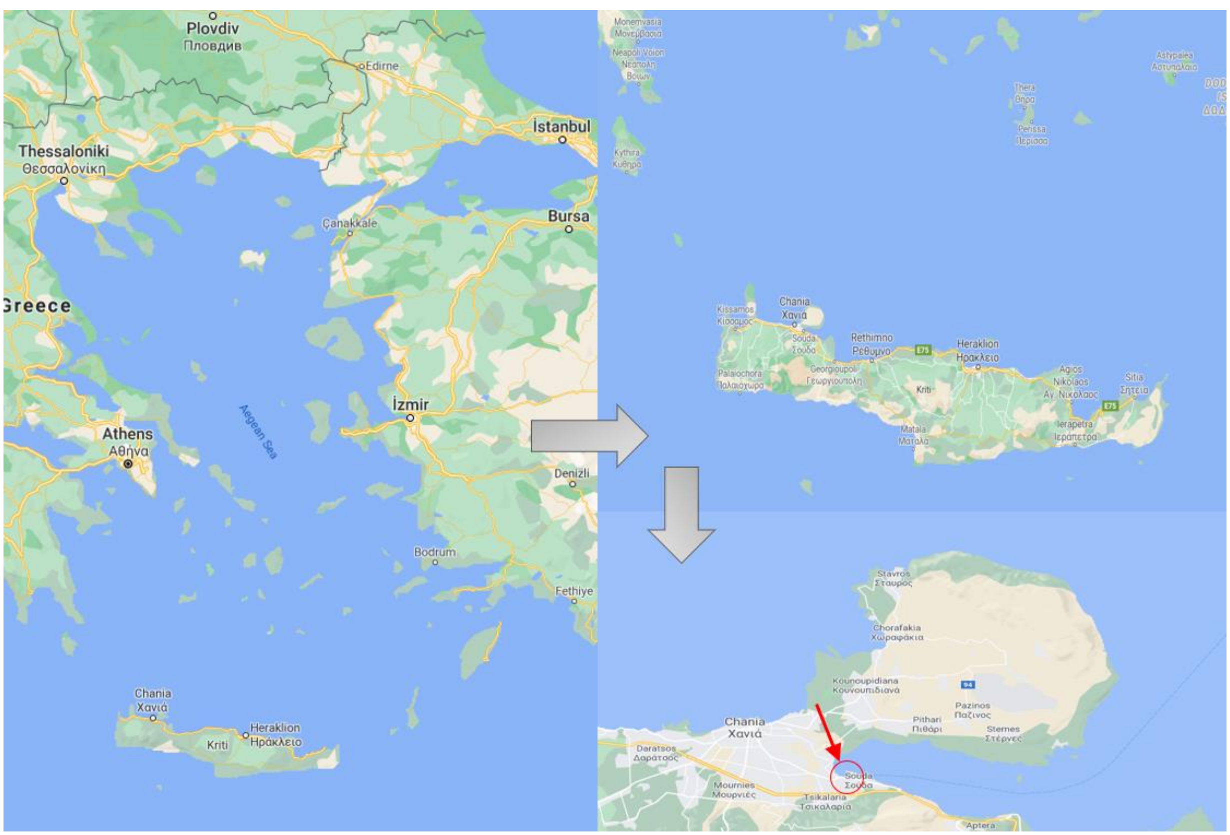


Figure 5.25. The geographical location of the Souda port

The actual energy demand data's acquisition and utilisation are among the crucial innovations of this research study compared to most past studies, let alone the collaboration with the port's personnel to install the smart metering systems. Specifically, the research team acquired and used actual data regarding every aspect of the research study, such as the total port's hourly energy demand, the energy cost, and the proposed technologies' regional pricing.

Seaports' energy demand is dynamic due to their complex operations; the various subsystems and the uncertain factors (weather conditions, tourism) strongly affect the energy consumption, establishing a stochastic nature that can be barely predicted. The stochastic aspect is handled and eliminated by utilising the 5-year average of 15-min port's energy demand data. The actual 5-year average port's demand profile was analysed, modelled, and integrated into the HOMER tool. An extra 30% of energy was integrated into each timestep data to increase the results' reliability, including the commercial port's energy demand; there are only monthly data available regarding this port's part.

The port's actual energy demand data were acquired by installing smart metering systems in the port infrastructures in collaboration with the port's personnel, enabling the acquisition of a 5-year hourly energy-demand time-series; the energy demand data include all the port operations that use electricity (lighting, vessels, buildings, etc.). The average fixed energy cost is modelled and integrated into the software by studying the monthly port's electricity bills for the past five years. The communication with the Harbour Management Organization of Prefecture of Chania contributed to the formulation of the final 35 examined scenarios.

There are no sudden hourly high energy demand peaks; the average hourly energy consumption is usually between 50 to 150kWh (Figure 5.26). Unexpectedly, the daily profile showed that the energy demand is higher during the winter and the high tourism periods (July-August). The port's average annual demand is 874,613kWh, which equals

2,396.236 kWh/d, while the peak energy demand value (194.36kW) is detected during a night hour in August. The heatmap also proved those mentioned above. The port is energy-supplied by the island's electricity grid; there are no in-situ RES to contribute to the port's energy demands.

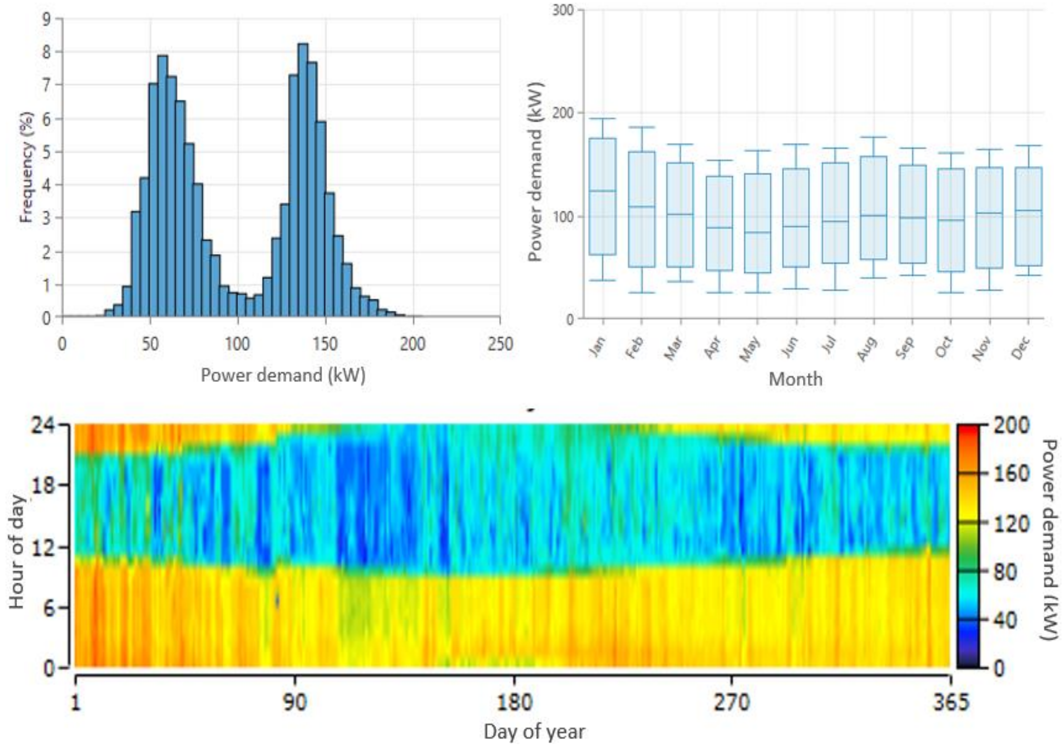


Figure 5.26. Souda's port hourly and monthly energy consumption

The renewable resources' availability significantly impacts the HRES efficiency. The available renewable resources potential is retrieved by the National Aeronautics and Space Administration's (NASA) POWER database and are compared to ground-level measurements conducted by the research team for validation purposes; the deviations were lower than 10%. Figure 5.27 shows the low frequency of extreme wind speed events (histogram) and the mean daily wind speed's fluctuation; the average wind speed is 6.26m/s. PV production is proportionate to the solar radiation and the sky clearness index; their monthly values are presented in Figure 5.28. The average daily solar radiation is 5.28kWh/m^{2}day, indicating the high solar availability in the port's surrounding area.

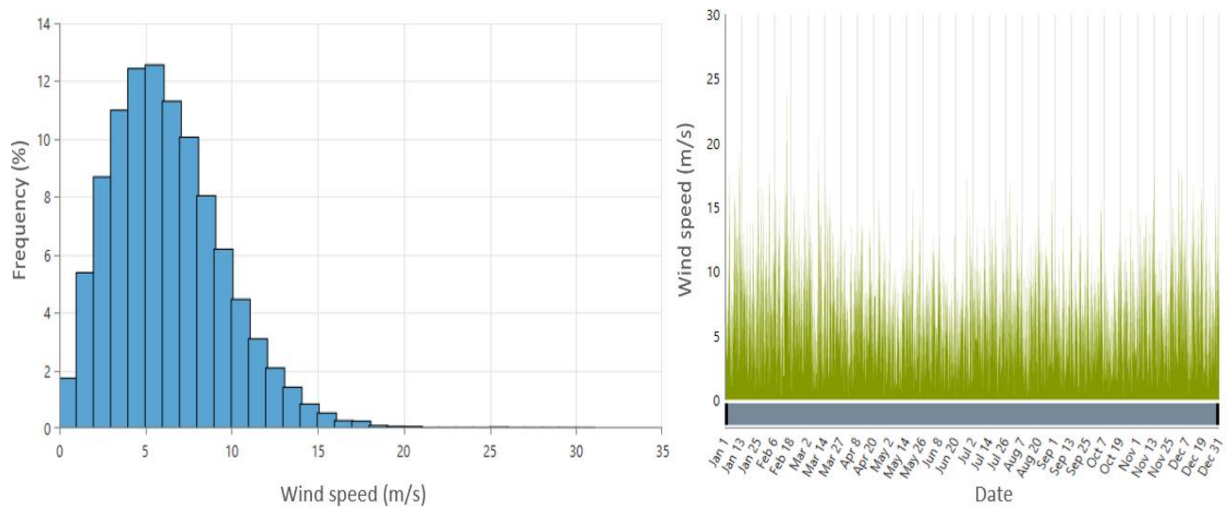


Figure 5.27. Histogram of mean hourly wind speed and area chart of the mean daily wind speed

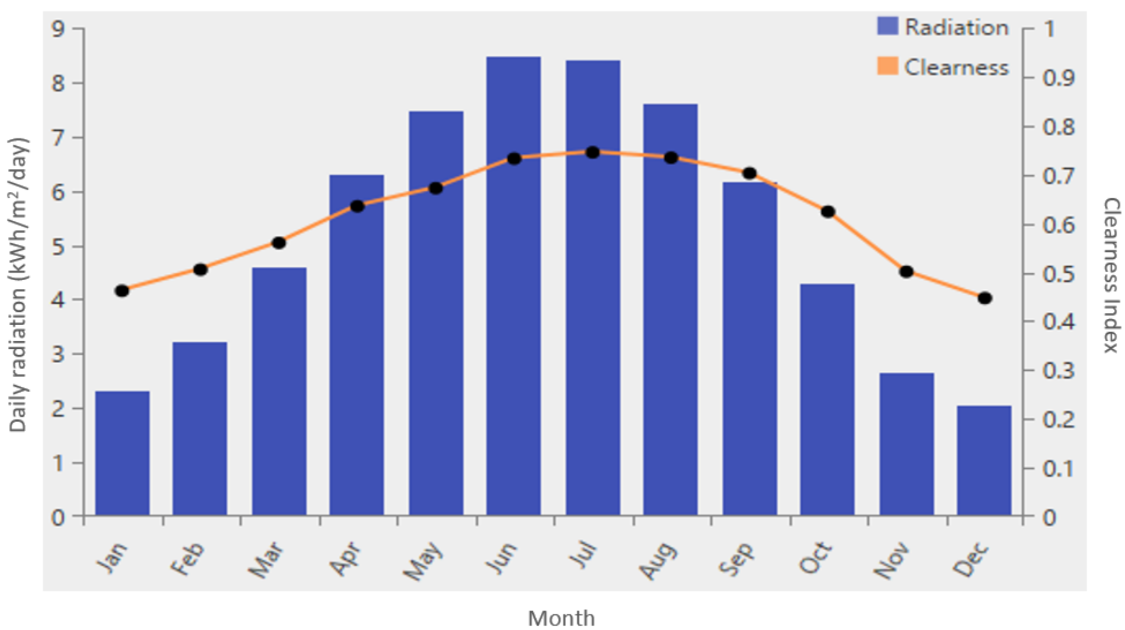


Figure 5.28. Mean monthly solar radiation and clearness index of the port's area

5.2.2 Optimal HRES sizing according to the three sustainability pillars methods

5.2.2.1 Optimal HRES sizing main concept and flowchart

The methodology was split into four major phases to satisfy the three sustainability pillars: environmental quality, social acceptance, and economic prosperity (Figure 5.29).

The first step refers to the case study selection, which is described later in this chapter.

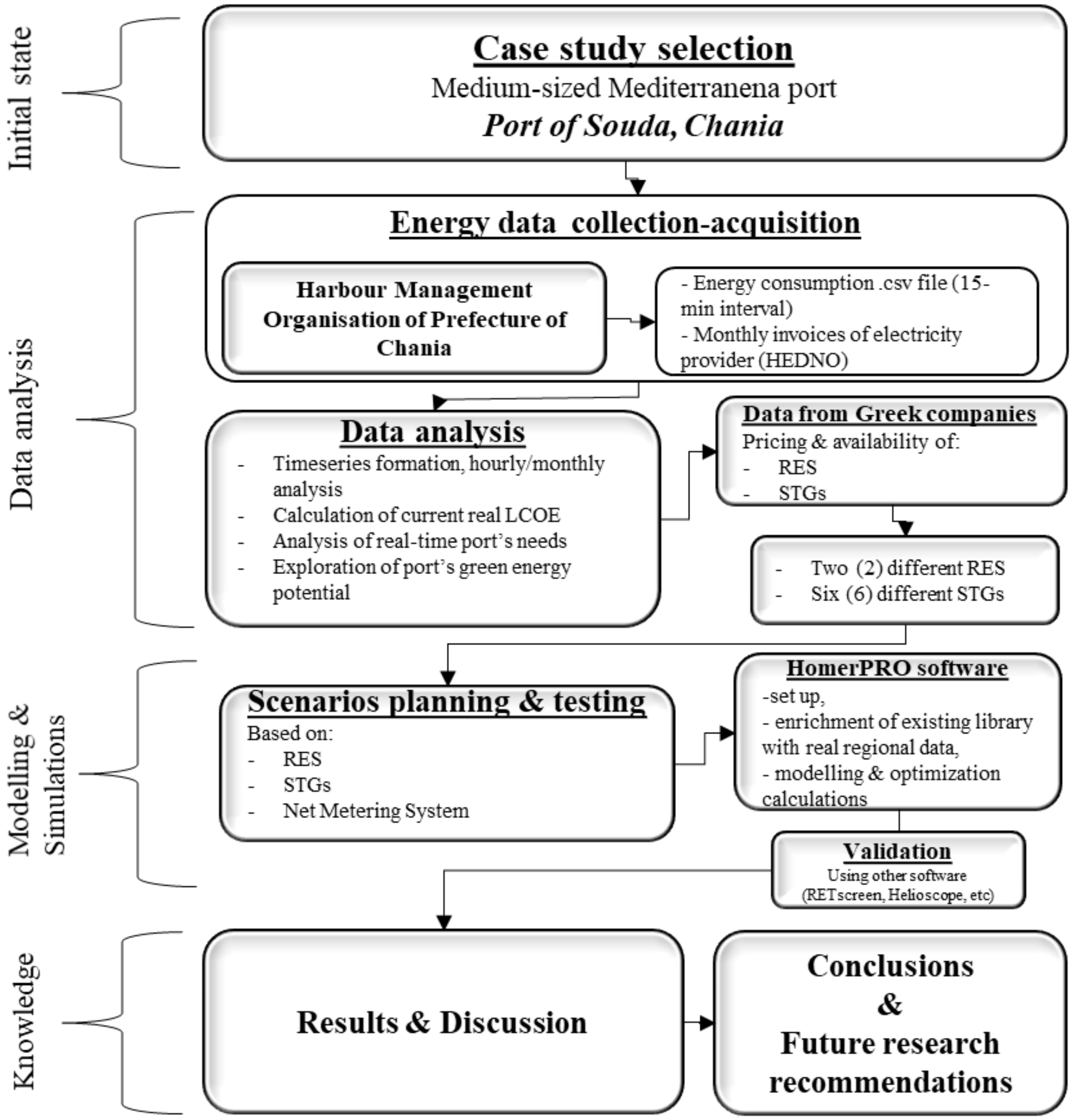


Figure 5.29. Flowchart of the research methodology

5.2.2.2 Data acquisition and analysis: Energy profile formulation

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5.2.2.3 Optimal HRES sizing modeling and simulation

The third step represents the scenarios conceptualisation and data processing in collaboration with the port's personnel. The examined scenarios were based on three fundamental parameters: RES type, ESSs type (Lead-Acid batteries (LAs) and Vanadium Redox Flow Batteries (VRFBs)), and the functionality of the grid's Net Metering (NM) functionality (Table 1). Thirty-five scenarios were simulated, compared, and evaluated, aiming to feature the optimal solution. Various constraints were considered, such as the annual capacity shortage, the grid's NMS legislation limits for the study area, and the technical constraints of the proposed technologies (i.e., ESS charging/discharging constraints). The optimal solution is obtained after simulating the scenarios, according to the inputs and the constraints, aiming to minimise the proper index for the three sustainability criteria. Indicatively, more than 800 cases per scenario were simulated and placed in the candidate pool.

The power output of the WT is calculated by Equation 23. P_r is the rated power of the WT, V_r is the rated wind speed (m/s), $V_{cut\text{-}in}$ is the cut-in speed, and $V_{cut\text{-}out}$ is the cut-out speed.

$$P_{WT} = \begin{cases} 0 & V < V_{cut-in} \; and \; V \geq V_{cut-out} \\ \dfrac{P_r \times (V - V_{cut-in})}{(V_r - V_{cut-in})} & V_{cut-in} \leq V \leq V_r \\ P_r & V_r \leq V < V_{cut-out} \end{cases} \quad (23)$$

V is the actual wind speed that varies with the WT's hub (Equation 24). V_{base} is the wind speed at the base height H_{base}. The exponent α represents climate conditions (season, time of the day, temperature, roughness); α often equals 0.143 under steady wind speed conditions. The WT's output power is multiplied with the density ratio, as shown in Equation 25. The symbol ρ represents the actual air density, and the air density at Standard Test Conditions (STC) is symbolised as ρ_0 (1.225 kg/m^3).

$$V = V_{base} \times \left(\frac{H}{H_{base}}\right)^{\alpha} \quad (24)$$

$$P_{WT} = \left(\frac{\rho}{\rho_0}\right) \times P_{WT,STP} \quad (25)$$

The PV power output is calculated by Equation 26 [363]. Y_{PV} is the PV array's rated capacity (kW), f_{PV} is the derating factor of the PV in percentage, G_T is the current timestep's solar radiation in kW/m^2, $G_{T,STC}$ is the incident radiation at STC, α_Q is the power's temperature coefficient (%/°C), T_C is each timestep's cell temperature of the PV (°C), and $T_{C,STC}$ is the PV's cell temperature under STC (25 °C). The derating factor is being used due to the PV arrays' possible power losses due to soiling, wiring, and aging.

$$P_{PV} = Y_{PV} \times f_{PV} \times \left(\frac{G_T}{G_{T,STC}}\right)[1 + a_\rho \times \left(T_c - T_{C,STC}\right) \quad (26)$$

Three different types of ESS are examined. They are used to store the surplus RES energy and serve the PS technique. The ESS energy can be estimated using Equation 27; $Q_{ESS,0}$ is the initial ESS charge, V_{ESS} is the battery's voltage, and I_{ESS} is the ESS current.

$$Q_{ESS} = Q_{ESS,0} + \int_0^t V_{ESS} \times I_{ESS} dt \quad (27)$$

The ESS's state-of-charge is given by Equation 28; $Q_{ESS,\ max}$ is the maximum allowable ESS's charge power, estimated using the kinetic battery model (Equations 29, 30, 31, and 32); $\eta_{ESS,c}$ is the ESS's efficiency [364]. k is the storage rate constant (h^{-1}), Q_1 is the ESS's available energy in the initial time step (kWh), Δt is the timestep's duration (h), Q is the initially available energy (kWh), c is the ESS's capacity ratio, a_c is the ESS's maximum charge rate (A/Ah), $Q_{ESS,max}$ is the total ESS's capacity (kWh), N_{ESS} is the number of ESS, I_{max} is the ESS's maximum charge current (A), and V_{nom} is the ESS's nominal voltage.

$$B_{SOC} = \frac{Q_{ESS}}{Q_{ESS,max}} x100 \quad (28)$$

$$Q_{ESS,max} = \frac{\min\left(P_{ESS,max,kbm} \times P_{ESS,max,mcr} \times P_{ESS,max,mcc}\right)}{\eta_{ESS,c}} \quad (29)$$

$$P_{ESS,max,kbm} = \frac{k \times Q_1 \times e^{-k\times\Delta t} + Q \times kc(1 - e^{-k\times\Delta t})}{1 - e^{k\times\Delta t} + c(k \times \Delta t - 1 + e^{-k\times\Delta t})} \quad (30)$$

$$P_{ESS,max,mcr} = \frac{1 - e^{-\alpha_c\times\Delta t} \ \ (Q_{ESS,max} - Q_{ESS})}{\Delta t} \quad (31)$$

$$P_{ESS,max,mcc} = \frac{N_{ESS} \times I_{max} \times V_{nom}}{1000} \quad (32)$$

Lastly, the bi-directional inverter's power output is given by Equation 33. P_{out} is the output power on the AC grid; P_{in} is the input power to the inverter on the DC grid, η_{inv} is the inverter's efficiency. In this study, the inverter's efficiency is taken as 0.95.

$$P_{out} = P_{in} \times \eta_{inv} \quad (33)$$

The total system's cost is defined by the sum of the PV costs (C_{pv}), the WT costs (C_{WP}), the electricity grid's cost (C_{grid}), the battery's cost ($C_{battery}$), and the converter's cost (C_{conv}) (equation 34):

$$C_{system} = C_{PV} + C_{WT} + C_{grid} + C_{battery} + C_{conv} \quad (34)$$

The capital, replacement, O&M, grid's energy, and fuel costs are included. No emission penalties were considered. Revenues include salvage value, and grid sales revenue are calculated using equation 35:

$$C_{NPC} = \frac{C_{ann,total}}{CRF(i, n_{pro})} \quad (35)$$

Besides, the total NPC is used to calculate the Levelised Cost of Energy (LCOE) by dividing it by the total electric load served (E_{served}) (equation 36) [363].

$$LCOE = \frac{NPC}{E_{served}} \quad (36)$$

Where $C_{ann,\ the\ total}$ is the total annual cost (€/year), CRF is the capital recovery factor (equation 37), i is the discount rate (%) (equation 38), N is the number of years. Where the discount rate is i=8.0%, and the inflation rate is f=2.0%.

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (37)$$

$$i = \frac{i' - f}{1 + f} \quad (38)$$

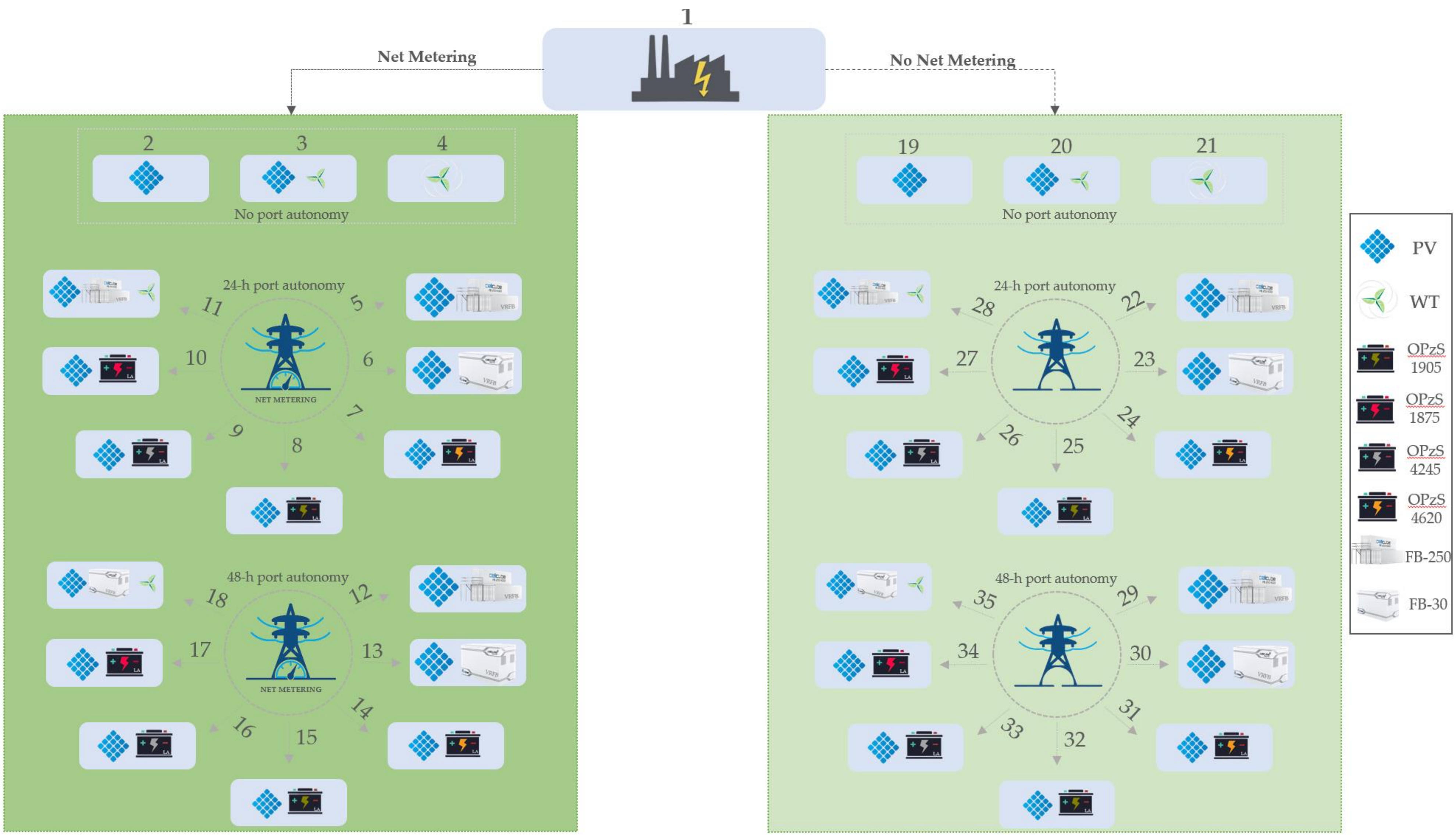

Figure 5.30. Description of the examined scenarios

Figure 5.30 depicts the incorporated technologies of each scenario. The concept is to split the study's outcomes into two parts regarding each electricity grid's case and three sub-parts regarding the port's energy autonomy. Two types of RES and two types of ESS were examined; two models of VRFB ESS and four models of LA ESS. The last scenario of each case suggests a PV/WT/ESS HRES according to the past scenarios' findings. The technical specifications of the examined technologies are presented in Table 5.4 and Table 5.5.

To evaluate the HRES, the energy Payback Period (PP), the Internal Rate of Return (IRR), and the Return on Investment (ROI) are used (equations 39, 40, 41):

$$PP = \frac{C_{init}}{C_{af}} \quad (39)$$

$$NPV = 0 = \sum_{t=1}^{T} \frac{C_t}{(1 + IRR)^t} - C_0 \quad (40)$$

$$ROI = \frac{\sum_{I=0}^{n_{pro}} C_{af,ref} - C_{af}}{n_{pro}(C_{cap} - C_{cap,ref})} \quad (41)$$

Where C_{init} is the initial investment, C_{af} is the annual cash inflow, $C_{af,\ ref}$ is the nominal annual cash flow for the baseline, n_{pro} is the project lifetime in years, C_{cap} is the capital cost of the initial-current system, and $C_{cap,\ ref}$ is the baseline's capital cost.

The GHGs are proportionate to the island's energy mix alongside the appropriate indexes per pollutant (equation 42). The island's energy mix is calculated using the most recent data acquired from the energy supplier (HEDNO). The appropriate Life Cycle Analysis (LCA) GHG indexes are used for the proposed technologies (Table 5.3). Finally, the vast majority (66.58%) of the island's energy generators consume crude oil, 11.95% consume diesel, while the installed RES generates the rest 21.47%.

$$Emissions\left(\frac{tn}{y}\right) = \frac{E_{grid}\left(\frac{kWh}{y}\right) \times Pollutant\ Index\ (g\,\frac{CO_{2eq}}{kWh})}{10^6} \quad (42)$$

Each technology's environmental impact is quantified using the $CO_{2,\ eq}$ index calculated by the most recent Global Warming Potential (GWP) factors provided by the Intergovernmental Panel on Climate Change (IPCC), a hundred-year time frame.

PVs have a significantly low life-cycle environmental footprint, offering significant environmental advantages relative to conventional fossil fuel or even nuclear technologies; the major pollutants are Carbon dioxide (CO_2), Dinitrogen monoxide (N_2O), Methane (CH_4), and chlorofluorocarbons (CFC) [365]. The GWP of these pollutants is 1, 298, 25, and 4750–14,400, respectively [366]; each suggested technology's Carbon Footprint (CF) is given by equation 43:

$$CF_S = \frac{\sum_{y \in GHG} \times GWP_y \times EM_y}{E_P} \; (43)$$

Index S represents the technology (i.e., PV, WT, ESS); CF_{PV} stands for the PV's CF; index y signifies each pollutant; GWP_y is the GWP factor of the pollutant y; EM_y corresponds to the emissions (direct and indirect) of the technology's life cycle. Lastly, E_P refers to the annual energy produced by the technology. The CF is measured in $gCO_{2,eq}$/kWh.

The calculation of the electricity grid's CF is based on equation 44 [367,368]:

$$CF_{DS} = F_{PE} \times F_D \times F_{FF} = 0.989 \times 0.785 = 0.776 kg \frac{CO_{2,eq}}{kWh} \; (44)$$

The primary energy factor (F_{PE}) equals 2.9 and is used to convert the final to primary energy (factory-side); the diesel factor (F_D) equals 0.989 $kgCO_{2,eq}$/kWh; the RES penetration is 21.5%, and thus the fossil fuels' factor (F_{FF}) is 78.5%. Based on past LCA studies, the CF_{PV} ranges from 30 to 100 $gCO_{2,eq}$/kWh. Recent studies have indicated that the mean CF_{PV}, for Europe is 37.3 $gCO_{2,eq}$/kWh [369]. As for the ESS, the LAB's CF equals 24,250 $gCO_{2,eq}/kWh_{cap}$, while the VRFB's CF is 38.2 $gCO_{2,eq}$/kWh [370]. Last but not least, WT's CF ranges from 15 to almost 50 $gCO_{2,eq}$/kWh [371]. The CF values for this research are presented in Table 5.3. Lastly, the net energy was calculated using Equation 45:

$$Net\ Energy = E_{grid} - E_{PV} - E_{WT} \; (45)$$

Table 5.3. CF factors for the proposed technologies

	Technology					
	Electricity Grid	PV	Converter	WT	LAB ESS	VRFB ESS
CF factor [$gCO_{2,eq}$/kWh]	2,25	37.3	26,300[1]	40	24,250[1]	38.2

[1]per kWh of system's installed capacity

Table 5.4. Technical specifications of the proposed ESS

Technology	Model	Nominal capacity [kWh]	Maximum capacity [Ah]	Voltage (V)	Installation costs [€/pc]	Lifespan [y (cycles)]
Lead Acid	Sunlight OPzV 4245	8.88	4440	2	1561.65	20 (2000)
	Sunlight OPzV 1875	3.95	1980	2	648.20	20(2000)
	Sunlight OPzS 4620	9.54	4770	2	1313.45	20(2000)
	Sunlight OPzS 1905	3.97	1990	2	549.84	20(2000)
VRFB	Gildemeister 250kW-4h CELLCUBE® FB 250-1000	1240	276	700	272,800[1]	25(3000)
	Gildemeister 30kW-100kWh CELLCUBE® FB 30-100	100	1770	48	22,000[1]	25 (3000)

[1]The costs of VFRBs were calculated based on [372–374]

Table 5.5. Technical specifications per employed RES

System	Proposed location	Proposed model	Efficiency (%) / Max power output (kW)	Area/kWp (m^2) / Hub height (m)	Installation costs [€/ kWp]		Lifespan [y]
PV (incl. inverter)	• roofs • newly-created carports • existing unused port lands through the grid's Virtual NMS	SunPower X21-335-BLK (SMA59.86)	21%	1.63	0-1 kWp	1400	20
					1-10 kWp	900	
					10-50 kWp	800	
					50-100 kWp	750	
					100-500 kWp	700	
					>500 kWp	600	
WT	• Existing unused port lands through the grid's Virtual NMS • off-shore installations	Eunice Thetis 50kW	54 @ 14-17 m/s	22.03	1 pc	4200	20
					5 pcs	3600	

The assumptions for this study are as follows [375]:

- The Greek market data for the technologies were obtained from experienced Greek suppliers, except for the VFRBs;
- The average energy cost equals 0.16€/kWh, including the taxes, the power rates, and the fixed rates of the power-supplier;
- The NMS's cost is not taken into account due to its scarce impact on the total NPC;
- The AC-DC converter's cost was included in the total PVs procurement cost;
- The solar power output was set to 25%, while the wind power output was set to 50%;
- The examined LA ESS are designed to operate for 3000 complete life cycles on a 50% Depth of discharge (DoD) and 2000 complete life cycles on 80% DoD.

Therefore, it is assumed that less than 120 complete life cycles occur yearly. This assumption is being strengthened because a maximum DoD of 80% is commonly used for grid-connected energy systems and a maximum DoD of 50% for off-grid systems.

5.2.2.4 Knowledge acquisition: Results and discussion

After simulating all the specified scenarios, the optimal scenario for each one of the criteria is picked (among the pool of feasible solutions), demonstrated, and compared to each other. Also, the optimal local scenario that concurrently satisfies all the specified sustainability criteria is picked and demonstrated, leading to solid and reliable outcomes.

5.2.3 Results of the optimal HRES sizing according to the three sustainability pillars

After simulating all the specified scenarios, a thorough techno-economic analysis and environmental assessment for each suggested HRES are presented. Also, a sensitivity analysis is conducted on five erratic parameters (i.e., Renewable Energy (RE) potential, discount rate, inflation rate, port's average energy demand and port's autonomy) evaluating the proposed system's stability. The schematic diagram of the proposed HRES is presented in Figure 5.31.

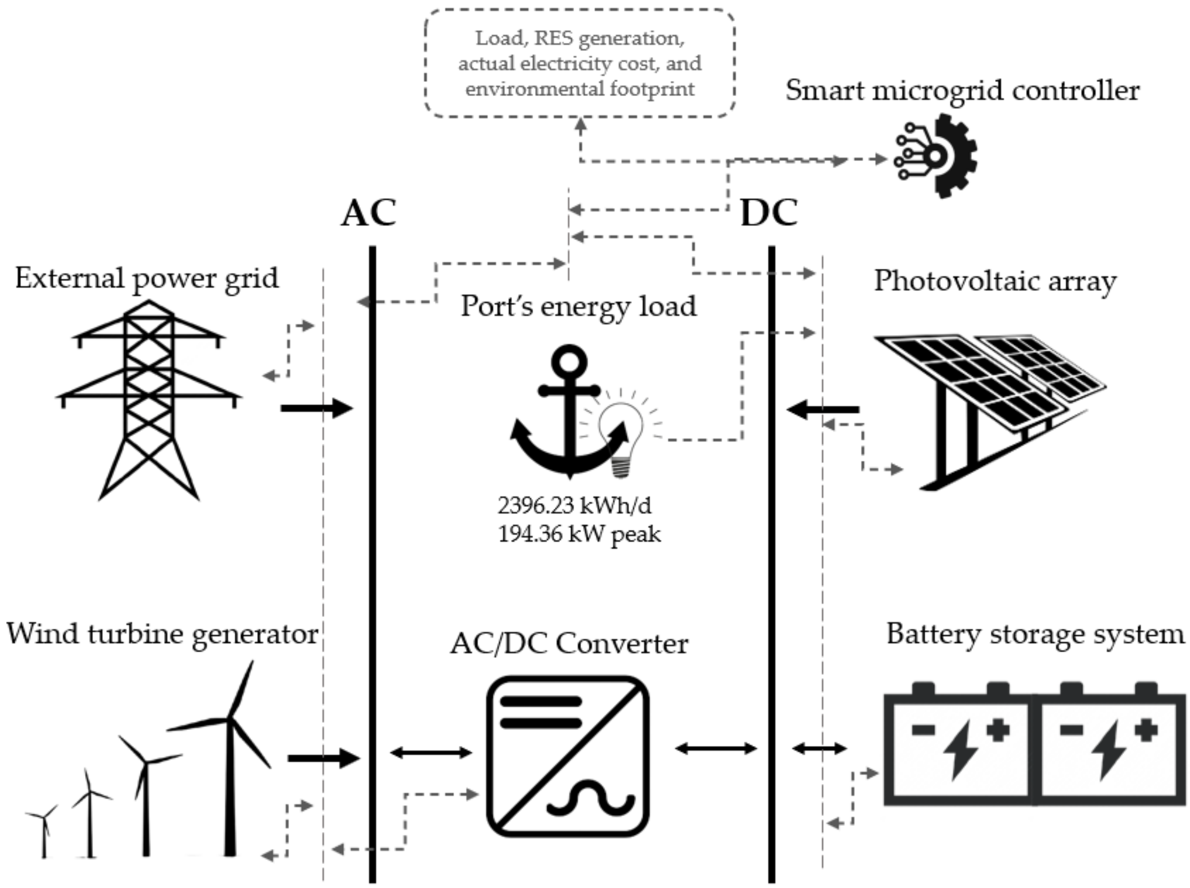

Figure 5.31. Schematic diagram of the proposed HRES

Two dispatch strategies are examined for the smart microgrid controller: (a) the Cycle Charging (CC) dispatch strategy, which is widely known for HRES cases, and the (b) the Load Following (LF) dispatch strategy, which is less known in the available literature.

The CC technique instructs the generator to run at maximum capacity or the grid to satisfy the load requirement while still charging the ESS. In each timestep, the most cost-effective mix of power sources is determined by measuring their fixed and marginal costs. As a result, there is no surplus energy produced or supplied; instead, the smart microgrid controller ramps up the generator's output or the grid's power in the most efficient way. The LF dispatch strategy charges the ESS as much as possible until reaching the specified setpoint and then deliver the surplus energy which could not be used locally into the electricity grid. In the opposite case, ESS will discharge as much as possible unless reaching the lower charge limit; the additional insufficient energy will be purchased from the electricity grid [363]. The outcomes of both the dispatch strategies are very similar due to the distinct characteristics of the suggested systems, so the CC strategy is picked as the optimal and used in this research; it is widely known for HRES cases (Figure 5.32). The baseline LCOE equals 16.0 c€/kWh. Also, the port's energy demand is almost 875MWh/y, resulting in almost 140,000€/y, and a bit less than 2,000tnCO2,eq, highlighting the need to transform the port into nZEP. Table 5.6 and Table 5.7 demonstrate the main results of the 35 scenarios that constitute the final candidate pool. For the sake of brevity, the outcomes of four scenarios are illustrated and discussed in this section. Indicatively, two optimal systems, in terms of LCOE and CF, for each grid's NM functionality case are presented.

After reviewing the tables, two scenarios are picked among the 17 available, based on the lowest LCOE and the lowest CF, for each case. The social acceptance criterion is satisfied by picking the scenarios providing at least 24-hr port's autonomy. This enables the electricity grid's alleviation during peak periods; the ESS provides the excess energy for the port services instead of the electricity grid.

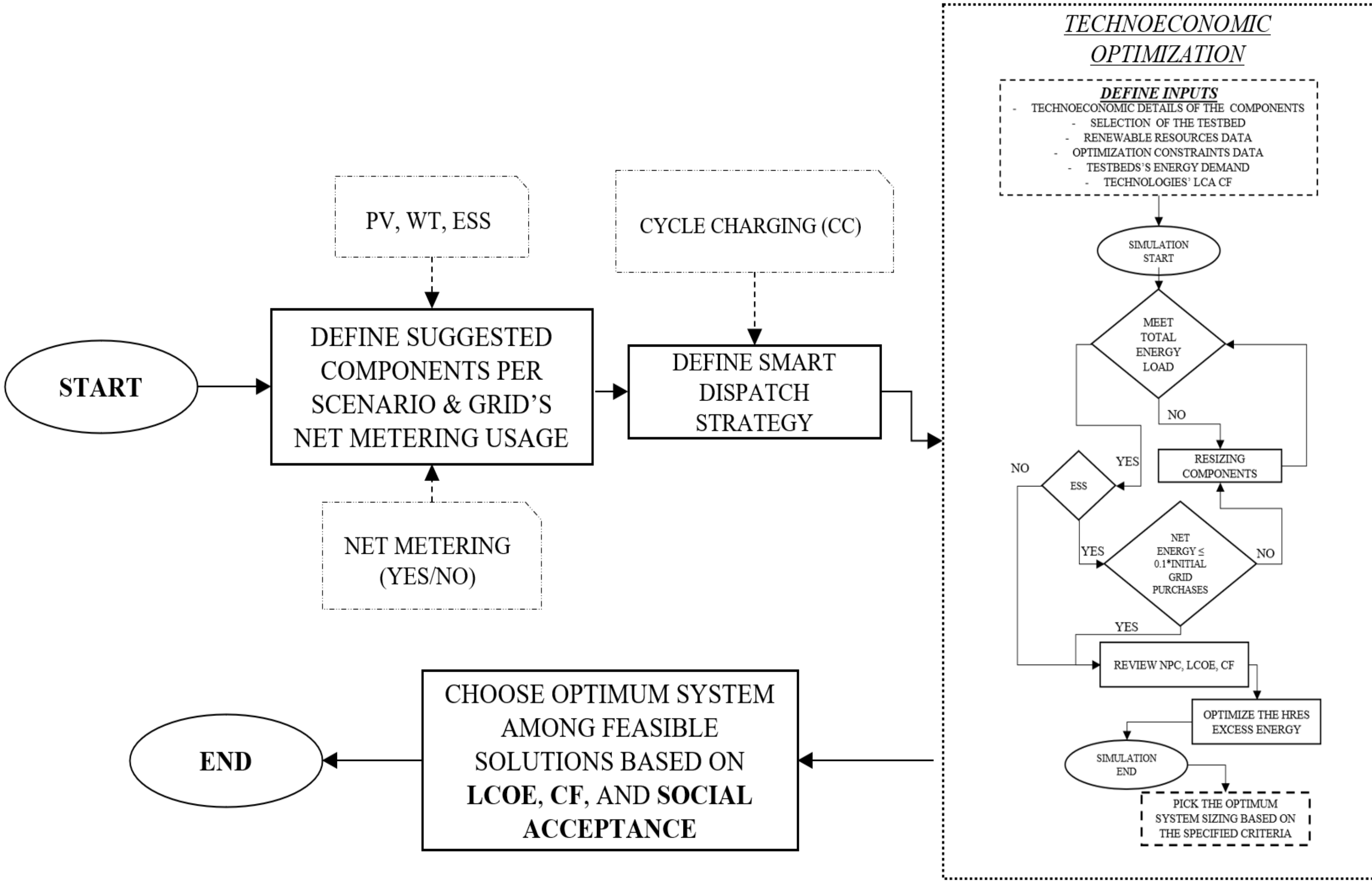

Figure 5.32. Proposed smart algorithm's flowchart

Table 5.6. Main characteristics of the optimal NM systems for each examined scenario

			RES		Technology				Economy						Energy	Environment		
Grid NM	a/a	Port operations Autonomy	Grid (%)	RF (%)	PV (kWp)	WT (qty)	Inverter (kWp)	ESS (model - qty)	NPC (M€)	Init. Cap. (k€)	ROI (%)	IRR (%)	PP (y)	LCOE (€/kWh)	Net energy (kWh/y)	Emissions during operation (tnCO2,eq/y) NO CF	Emissions during operation (tnCO2,eq/y) CF	gCO2,eq/kWh
Net Metering	1	**Baseline**	100	0					1.62		0	0	0	0.160	874,624	1967.9		
	2	No autonomy	39.8	60.2	502		643	x	0.416	350.9	34.4	38.4	2.6	0.022	-1,411	0	34.5	39.4
	3	No autonomy	36.6	63.4	449	1	600	x	0.613	524.8	21.4	25.6	3.9	0.033	-29,359	0	35.7	40.8
	4	No autonomy	32.9	67.1		7		x	1.480	1,245	5.9	8.7	9.2	0.091	29,479	66.33	33.8	38.7
	5	24-h autonomy	12.5	87.5	605		654	FB250 (2)	1.052	948.5	9.9	13.3	7.2	0.079	-431	0	62.4	71.4
	6	24-h autonomy	12.3	87.7	635		614	FB30 (24)	1.058	945.6	9.9	13.3	7.2	0.079	-226	0	65.1	74.4
	7	24-h autonomy	13.8	86.2	513		470	OPzS4620 (598)	1.362	1,140	6.8	9.7	9.3	0.103	-11	0	41.3	47.2
	8	24-h autonomy	13.8	86.2	513		400	OPzS1905 (1488)	1.625	1,175	5	7.5	11.2	0.123	-12	0	41.5	47.4
	9	24-h autonomy	13.8	86.2	513		400	OPzS4245 (638)	1.583	1,353	5	7.6	11.1	0.120	-13	0	41.2	47.1
	10	24-h autonomy	13.8	86.2	513		398	OPzS1875 (1481)	1.766	1,317	4	6.2	12.5	0.134	-1,199	0	41.4	47.3
	11	24-h autonomy	10.3	89.7	539	1	629	FB250 (2)	1.205	1,125	7.6	10.7	8.5	0.095	914	2.06	48.1	55.0

12		11.2	88.8	607		855	FB250 (4)	1.624	1,495	4.7	7.1	11.51	0.124	108	0.24	62.0	70.9
13		10.9	89.1	640		619	FB30 (48)	1.620	1,476	4.7	7.2	11.5	0.124	-430	0	64.6	73.8
14		12.4	87.6	513		636	OPzS4620 (1196)	2.300	1,927	1.8	3.0	17.4	0.177	-371	0	47.9	54.7
15	**48-h autonomy**	12.4	87.6	513		295	OPzS1905 (2976)	2.827	1,993	x	x	x	0.218	-541	0	47.9	54.7
16		12.4	87.6	513		295	OPzS4245 (1276)	2.744	2,349	0.7	1.2	21.5	0.211	-537	0	47.3	54.1
17		12.4	87.6	513		295	OPzS1875 (2962)	3.106	2,276	x	x	x	0.239	-83	0	47.7	54.6
18		9.2	90.8	563	1	445	FB30 (48)	1.811	1,648	3.7	5.9	12.7	0.141	-4,648	0	55.8	63.8

Table 5.7. Main characteristics of the optimal non-NM systems for each examined scenario

			RES		Technology				Economy							Energy	Environment		
Grid NM	a/a	Port operations Autonomy	Grid (%)	RF (%)	PV (kWp)	WT (qty)	Inverter (kWp)	ESS (model - qty)	NPC (M€)	Init. Cap. (k€)	ROI (%)	IRR (%)	PP (y)	LCOE (€/kWh)	Net energy (kWh/y)	Emissions during operation (tnCO2,eq/y) NO CF	Emissions during operation (tnCO2,eq/y) CF	gCO2,eq/kWh
Without Net Metering	1	**Baseline**	100	0					1.62		0	0	0	0.160	874,624	1967.9		2250
	19	No autonomy	62.7	37.3	217		210	x	1.527	155.4	17.8	21.6	4.6	0.115	495,993	1116.0	14.8	1292.9
	20		57.6	42.4	449	1	600	x	1.604	336.9	8.5	11.9	7.6	0.122	447,759	1007.5	35.7	1192.7
	21		73.0	27.0		2		x	1.787	382,5	4.3	6.5	10.8	0.155	633,154	1424.6	9.7	1639.9
	22	24-h autonomy	12.4	87.6	607		208	FB250 (2)	1.369	949.3	7.3	10.4	8.8	0.109	52,519	118.17	62.0	206.0
	23		13.1	86.9	614		185	FB30 (24)	1.385	935.0	7.3	10.3	8.9	0.113	89,792	202.03	63.1	303.2
	24		12.0	88.0	549		185	OPzS4620 (598)	1.662	1,160	4.7	7.2	11.5	0.127	-2,016	0	43.4	44.4
	25		12.0	88.0	549		280	OPzS1905 (1488)	1.925	1,193	3	4.8	14.3	0.140	-53,402	0	43.7	50.0
	26		12.1	87.9	549		280	OPzS4245 (638)	1.883	1,371	3.3	5.3	13.7	0.137	-53,401	0	43.4	49.7
	27		12.1	87.9	549		177	OPzS1875 (1481)	2.065	1,335	2.3	3.8	16.0	0.159	3,955	8.90	43.5	49.7
	28		10.4	89.6	536	1	290	FB250 (2)	1.506	1,124	5.8	8.6	10.0	0.117	-99	0	47.5	54.3

29	**48-h autonomy**	8.5	91.5	681		219	FB250 (4)	1.903	1,532	3.3	5.2	13.8	0.147	-14,589	0	66.1	75.6
30		9.5	90.5	678		453	FB30 (48)	1.905	1,495	3.2	5.2	13.8	0.139	-55,920	0	66.9	76.5
31		7.6	92.4	615		255	OPzS4620 (1196)	2.300	1,978	0.8	1.5	20.7	0.181	-123,309	0	54.2	62.0
32		7.5	92.5	616		237	OPzS1905 (2976)	3.077	2,044	x	x	x	0.222	-110,756	0	54.7	62.5
33		7.5	92.5	616		237	OPzS4245 (1276)	2.994	2,401	x	x	x	0.215	-110,745	0	54.2	61.9
34		7.6	92.4	616		850	OPzS1875 (2962)	3.357	2,328	x	x	x	0.227	-178,815	0	55.4	63.3
35		7.9	92.1	599	1	536	FB30 (48)	2.045	1,665	2.7	4.3	14.8	0.152	-61,896	0	58.3	66.7

5.2.3.1 HRES with the grid's NM functionality

Scenarios involving the grid's NM functionality operate the electricity grid as an ESS. There are no energy wastes, as the excess energy is transferred into the electricity grid if it cannot be consumed neither for the port's operations nor for the ESS charging. Thus, the GHGs deriving from the power plants near the port-cities are significantly reduced due to the high RE penetration; the fossil-fuel-generators do not operate at their maximum power. The port's social acceptance increases alongside the attractiveness of the port services because of the uninterrupted energy supply. The social acceptance's factor is satisfied as the optimal-picked systems can provide at least 24h of autonomy; the electricity grid is alleviated, leading to fewer failures and higher available resources during peak-demand periods.

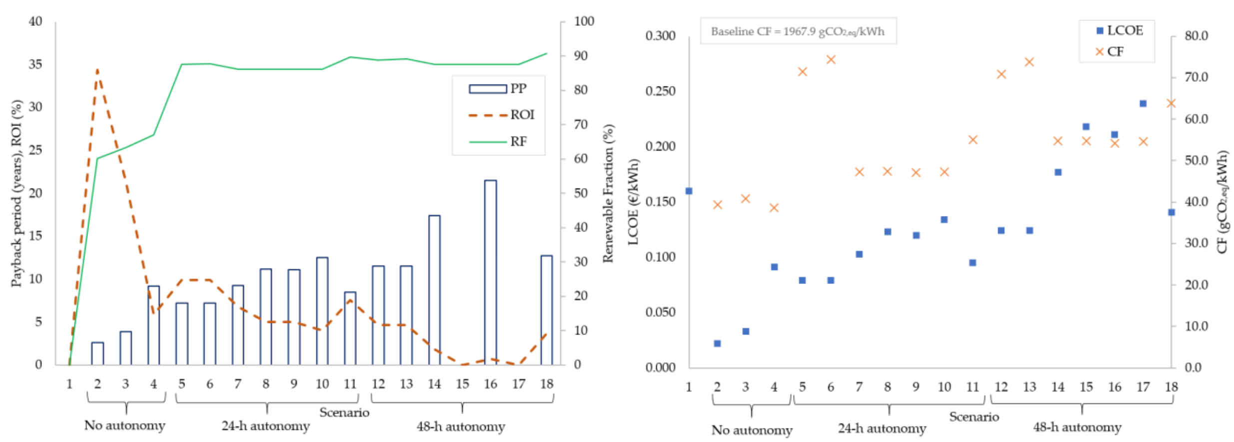

Figure 5.33. Examined scenarios' HRES financial and environmental outcomes for the NM case

The optimal HRES, from the economic point of view, is this of scenario 5 (Figure 5.33). The suggested HRES is comprised of 605kWp PVs, a 654kWp AC-DC inverter, and two pieces of Gildemeister's FB-250, providing at least 24-h port's services autonomy. It is the corresponding scenario to this of the non-NM case (scenario 22). Excess energy is not treated as a waste as it is calculated cumulatively to the annual energy balance.

The NM functions beneficially, in terms of LCOE, presenting the lowest energy costs among all the optimal-picked systems of all scenarios offering 24-h autonomy. Specifically, the LCOE of the proposed system is 7.9c€/kWh, while the PP equals 7.2y. These values are the lowest among the possible 24h scenarios due to the increased ESS efficiency and the grid's NM functionality. The LCOE is 50.6% lower than the baseline, which is substantial for such an initiative that provides 24h autonomy to the port's services. 71.4gCO2,eq/kWh are emitted during its operation, which is reduced by 96.8% compared to the baseline case. The optimal proposed system, on environmental terms, consists of 513kWp PVs, a 400kWp AC-DC converter, and 638 pieces of OPzS4245, providing 24-h autonomy. The LCOE is 52% higher than this of scenario 5, but still 25% lower than this of the baseline scenario; the LCOE is 12c€/kWh. The suggested system's CF is 47.1gCO2,eq/kWh, which is 97.9% lower than the baseline one and 34.1% lower than the optimal-picked on financial terms (scenario 5).

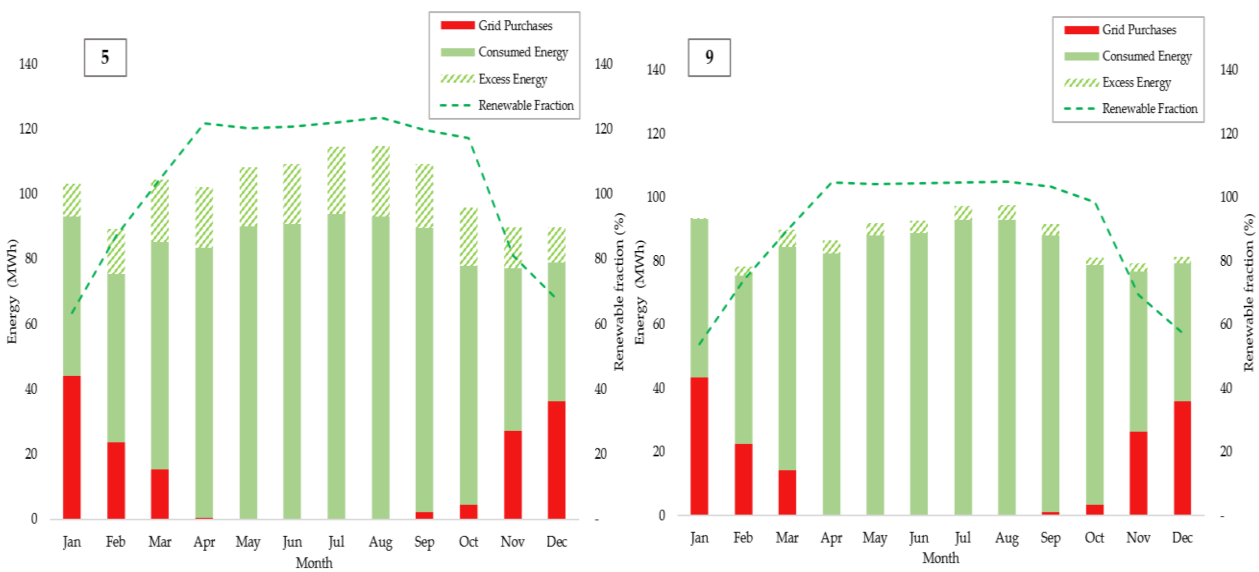

Figure 5.34. Monthly energy generation diagrams for the two optimal-picked scenarios for the NM case

The highest RE generation takes place during the summer months (Figure 5.34). Also, the high ESS and NM importance during the winter months, is highlighted by the low renewable fraction and the lower grid purchases compared to the baseline case. For scenario 9 on which another ESS type than scenario 5 is used, both the renewable energy fraction and the excess energy are lower. Unexpectedly, the grid purchases are slightly higher in scenario 5 than in scenario 9; the NM functionality shows that the net energy is negative in both cases.

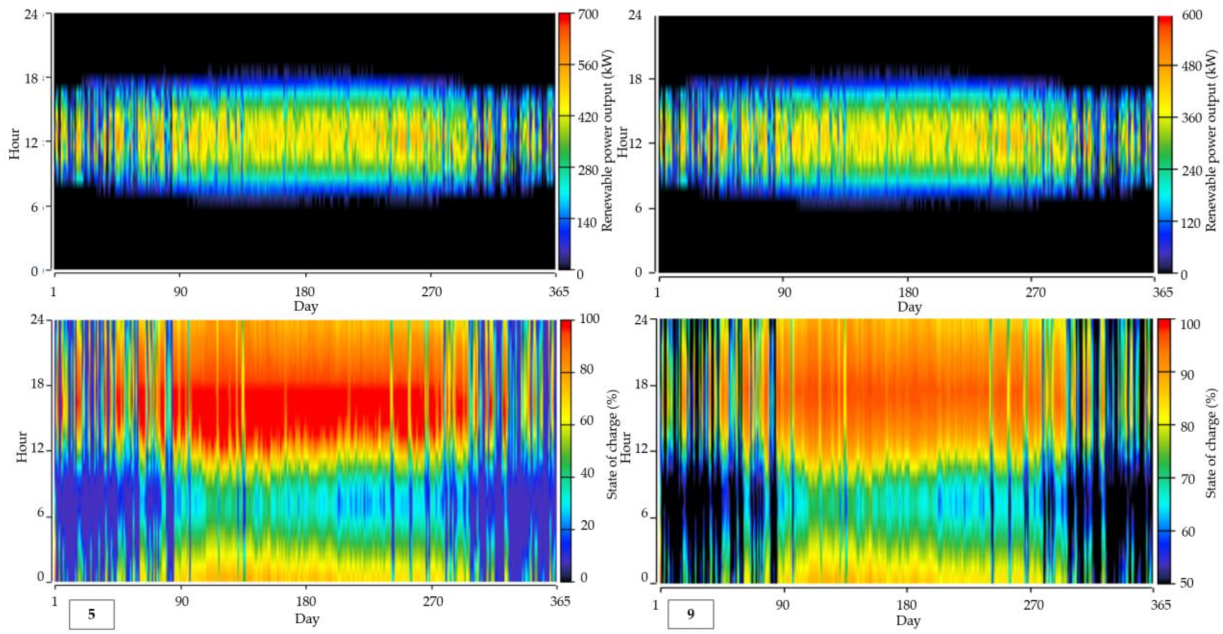

Figure 5.35. Heatmaps of the hourly renewable power output and state of charge for optimally-picked NM systems

There is no actual difference between the two cases for the high-RES production hours (Figure 5.35). The energy production scheme is the same for both cases; there is no energy generation during the night due to the absence of WTs. Although, the high amounts of generated energy during the day are enough to charge the installed ESS and provide all the required energy during the high peak-demand months. The RES power output is higher on the HRES of scenario 5 due to the higher installed power of the PVs.

For the HRES of scenario 5, it is clear that the PVs generate the energy to fully charge the ESS, according to the red colour in the heatmap (Figure 11). For the suggested HRES of scenario 9, the PVs cannot fully charge the ESS during the day-hours for that many instances as in scenario 5; more orange than red colour instances are occurring in the heatmap. The black spots depict that there is no enough stored energy in the ESS to serve the port's needs.

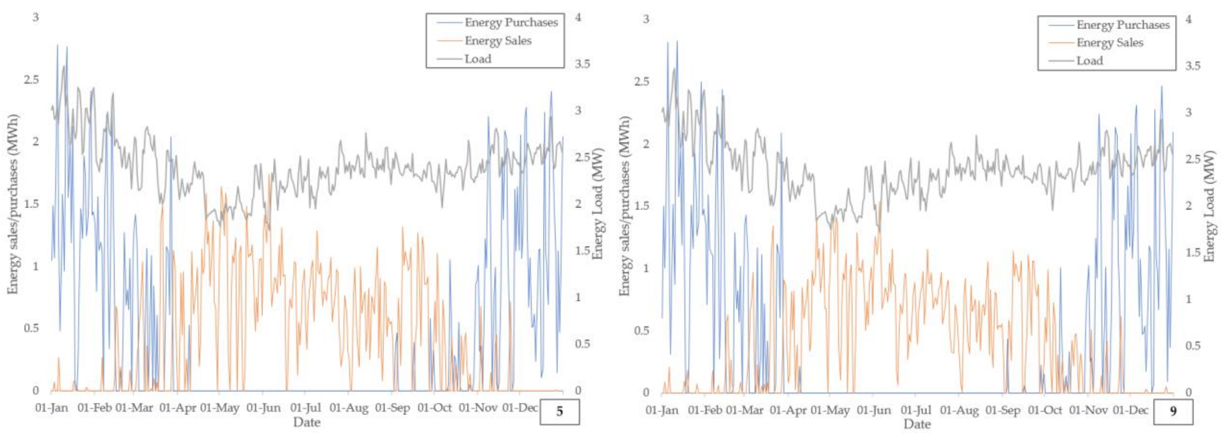

Figure 5.36. Daily grid sales and purchases for the optimal-picked systems for the NM case

The energy sales are calculated in the annual energy balance unalike the non-NM case. There is more excess energy in the HRES of scenario 5 compared to this scenario 9, justifying that the daily energy sales are higher in some cases (Figure 5.36). The energy purchases are almost the same, presenting some minor decreases in a few cases; they are more common in the winter months due to the inadequacy of RE generation. Besides, the higher energy sales are during the spring months due to the lower energy loads according to the lighting infrastructures responsible for more than 50% of the total energy demand. If either the discount or the inflation rate is reduced or increased, the financial terms of the initiative are greatly impacted. For both the NM optimal-picked systems, the annual net energy is negative, meaning that the grid purchases are lower than the grid sales; the positive GHGs are explicitly deriving from technologies' operation. The grid energy is counterbalanced from the RE generation. Also, both systems' LCOE reduction is significant, and the prospect of converting a port into nZEP seems to be viable and realistic.

The financial outcomes can be verified by the available past researches regarding other infrastructures, such as households, islands or even communities. The calculated LCOE is lower than the vast majority of past researches due to the utilization of actual cost data for the technologies in Greece and the high-RES penetration. Also, the social acceptance criterion is considered and satisfied. Consequently, the port's city economy flourishes by the port's activity, which is projected to rise; the port's attractiveness is increased being a nearly zero-energy infrastructure, offering unhampered services to its end-users.

5.2.3.2 HRES without the grid's NM functionality

The scenarios without the grid's NM functionality indicate the importance of incorporating ESS into HRES; the RE needs to be stored. The two optimal-picked systems refer to the scenarios incorporating 24-hr port's services autonomy (Figure 5.37).

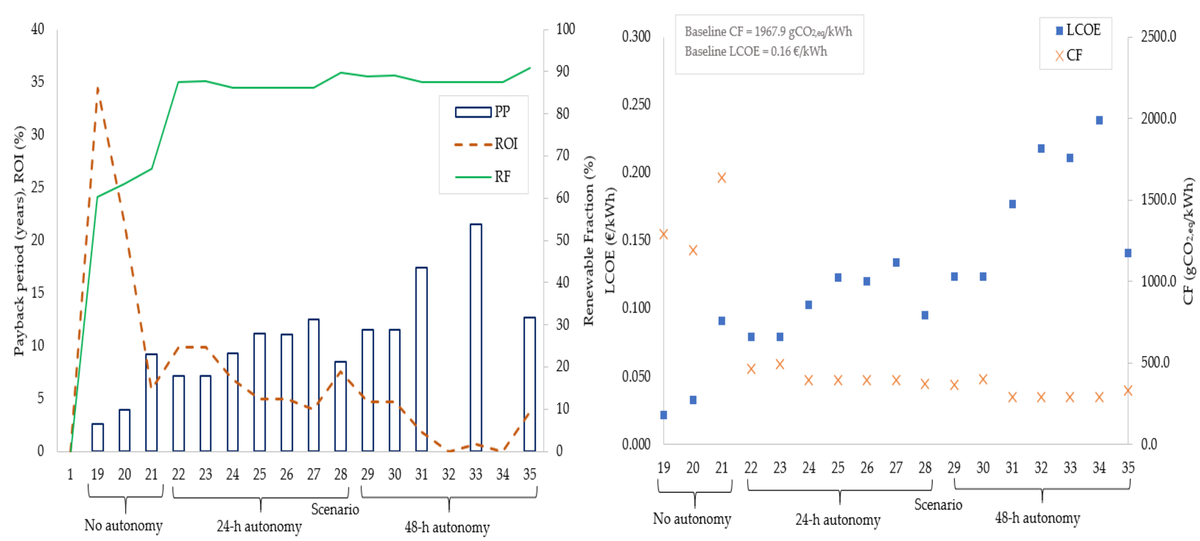

Figure 5.37. non-NM examined scenarios' HRES financial and environmental outcomes

The ideal HRES, on financial terms, is this of scenario 22; PVs of 607kWp are installed, a 208 kWp AC-DC inverter, and two pieces of Gildemeister's FB250 are incorporated. The port services can operate for at least 24-hr with no energy supply from the installed RES or the electricity grid. The system's LCOE is 10.9 c€/kWh, 32% lower than the baseline; the system's PP equals 8.8y, which is substantial, considering the 24-h services' autonomy. The port's CF (463.7gCO2,eq/kWh) is reduced by 79.4% compared to the baseline (2250gCO2,eq/kWh), establishing a modern, environmentally-friendly infrastructure harmonised with the most recent EU legislation. According to the conducted sensitivity analysis, if either the discount or the inflation rate are modified, the proposed system's financial outcomes are greatly impacted similarly to the previous case. Altering the renewable resources' potential indicated that the solar output highly impacts the HRES green energy due to the high PV penetration.

Meanwhile, the optimal HRES, on environmental terms, is this of scenario 28, which proposes to install 536kWp of PVs, a 50kWp WT, a 290kWp AC-DC inverter and two pieces of Gildemeister's FB250. This system scored the lowest CF among the other candidates (374.7gCO2,eq/kWh); it is 83.3% lower than the initial due to the high RES penetration and the lower grid purchases; WTs power output is not restricted to day-hours. Also, the system's LCOE equals 11.7c€/kWh, being slightly higher (7.3%) of the financial-optimal, but still lower than the initial one (26.9%).

Indicatively, Figure 5.38 depicts the system's monthly energy generation for both cases; Figure 5.39 demonstrates the hourly ESS state of charge for the two optimal-picked cases, while Figure 5.40 shows the daily energy purchases from the grid compared to the daily energy sales to the grid for both scenarios.

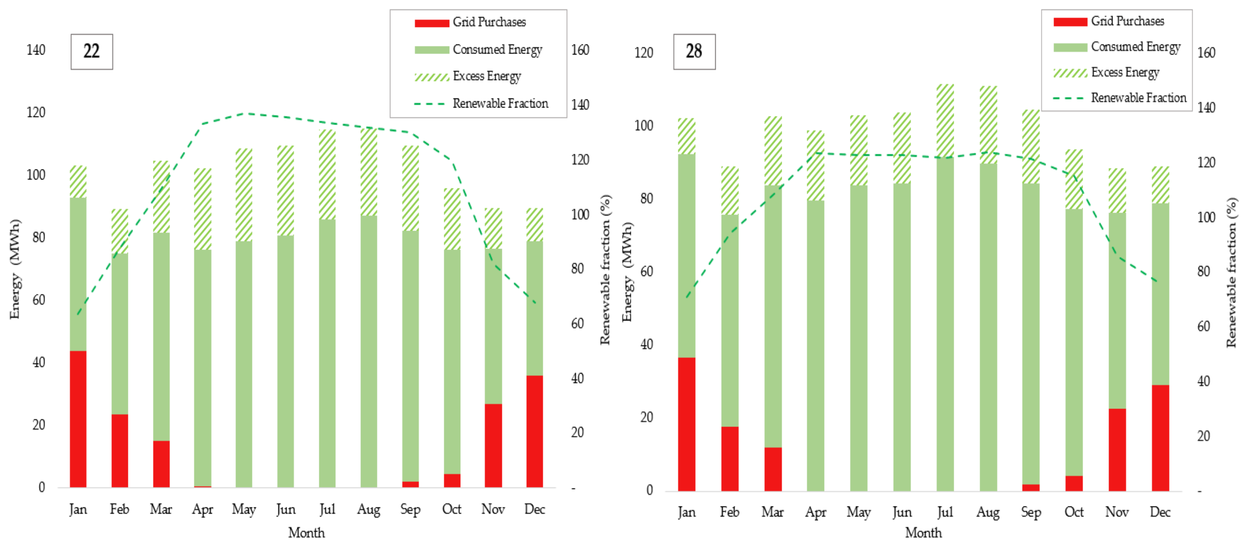

Figure 5.38. Monthly energy allocation diagrams for the two picked scenarios for the non-NM case

The high renewable penetration is evident during the summer months, when the PVs energy output is maximised. The high importance of ESS during the winter months for both the examined cases is evident as any excess energy is dumped to the electricity grid; in scenario 22, more PVs are installed compared to scenario 24, to cover the port's needs in cooperation with the ESS. Although a 50KWp WT is installed in scenario 28, more excess energy is provided to the grid on scenario 22; 259MWh of excess energy is dumped on scenario 22 compared to 210MWh of excess energy on scenario 28. Although the RES generates more energy in scenario 22, the grid sales are higher, leading to positive annual grid purchases, negatively impacting the system's CF. The ESS enable the asynchronous use of the RE during the night hours.

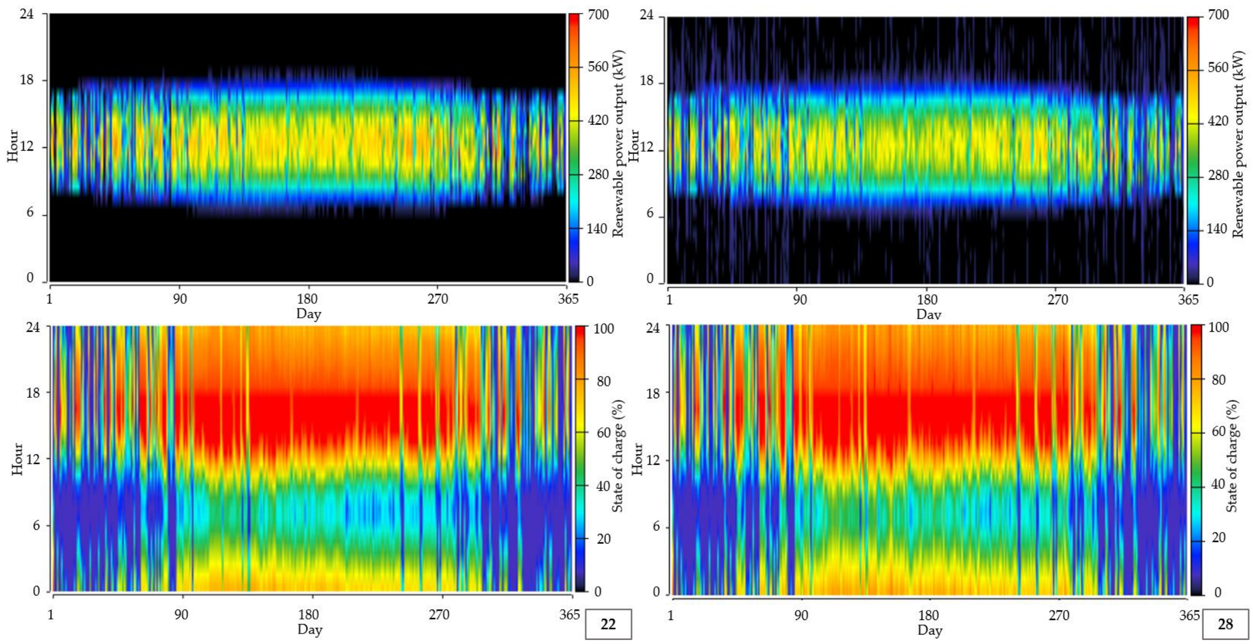

Figure 5.39. Hourly renewable power output and state of charge for optimally-picked non-NM systems

The ESS is fully charged during the summer because of the increased RE generation (Figure 5.39). Meanwhile, there is sufficient stored energy to cover the port's needs even during the night hours. For the installed WT that generates energy during night-hours, it contributes for only 10% of the total energy demand. Consequently, there is no need for grid purchases during the summer months, as the ESS can store all the surplus energy for future use. In addition, more energy is stored in the ESS by adding the WT, leading to a more stable system capable of covering even the unforeseen high-peak demands.

The main difference between the two scenarios is that in scenario 28, which is environmentally optimal, there is green energy generation during the night due to the WT that contributes to the ESS charging during the night at higher levels than in scenario 22, while also limiting their lower discharge levels during the day. There are higher amounts of stored energy during the summer months when the PVs production is maximised. There are great amounts of energy in the ESS during the spring and summer months, which are not used for the port’s needs during the day instead of the winter or autumn months. Nevertheless, the ESS stored energy is similar in both scenarios, proving their great importance for the port's operation, even when they are not needed to provide autonomy but to normalise the loads and alleviate the electricity grid. Thus, their role is catalytic for the port cities' economy and the unhampered, trouble-free and safety of the port services.

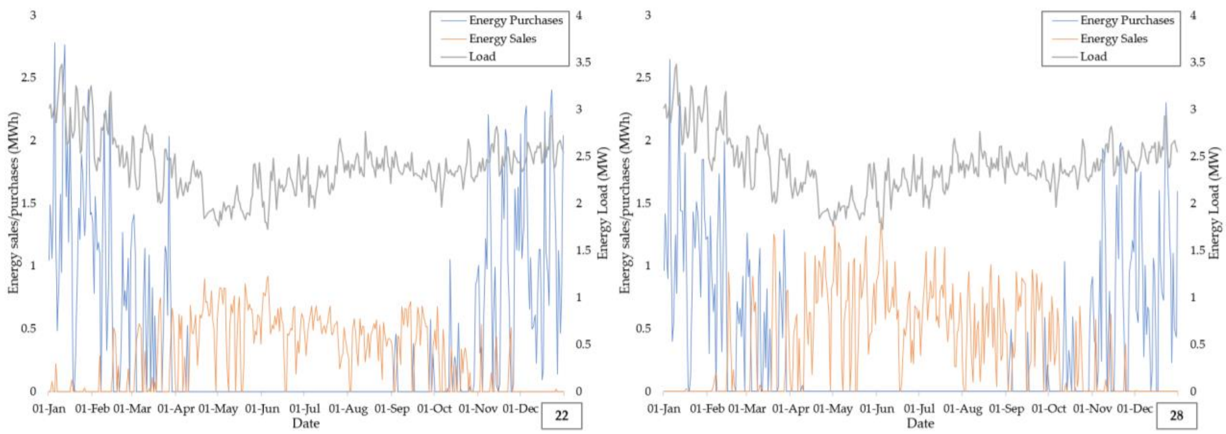

Figure 5.40. Daily grid sales and purchases for the optimal-picked systems for the NM case

Grid sales correspond to the energy that is not used anywhere due to the absence of the grid's NM function. Even for the optimal HRES sizing, it is impossible to self-consume all the energy generated; even the ESS cannot store all the RE energy leading to energy wastes. In the WT-case, the dumped energy is more than in scenario 22, while the energy purchases are lower due to the energy generation during the night-hours (Figure 5.39). Instead, there are days in which the grid purchases are much lower while the demand peaks are reduced. If the actual cost scheme had been integrated, the financial benefits would be even greater. The energy purchases are most common during the winter months, while the energy sales are higher during the summer. The excess energy is mainly during the day due to the increased production of PVs; this energy is fed to the grid without any profit for the port authorities. The grid purchases during the night are reduced in scenario 28 compared to scenario 22 due to the WT's existence. Altogether, the excess energy is higher for scenario 28 due to the greater RES penetration.

The conducted sensitivity analysis for both the grid cases, led to the same results; the renewable resources potential highly impacts the suggested HRES operation and the port's operations stability. Also, the higher the requested ESS autonomy, the higher the LCOE expected due to the initial increased capital. Lastly, the mean daily energy consumption highly impacts the port's CF due to the increased needs to be covered using energy from the electricity grid.

5.3 Introducing the cold-ironing technique into a small Mediterranean port by examining the efficiency of a hydrogen-based HRES

5.3.1 Case study's detailed description

According to the previously-mentioned typology, the selected case study is the small-sized port of Adamas in Milos Island (Figure 5.41). The port serves the island's inhabitants' needs, providing ferry transport to the mainland or other islands, such as Piraeus, Rethymno, Heraklion, and Syros. In addition, Adamas is the most developed tourist centre of Milos and is defined as the main reception point of tourists during the summer season. Therefore, it plays a crucial role in the island's economic development.

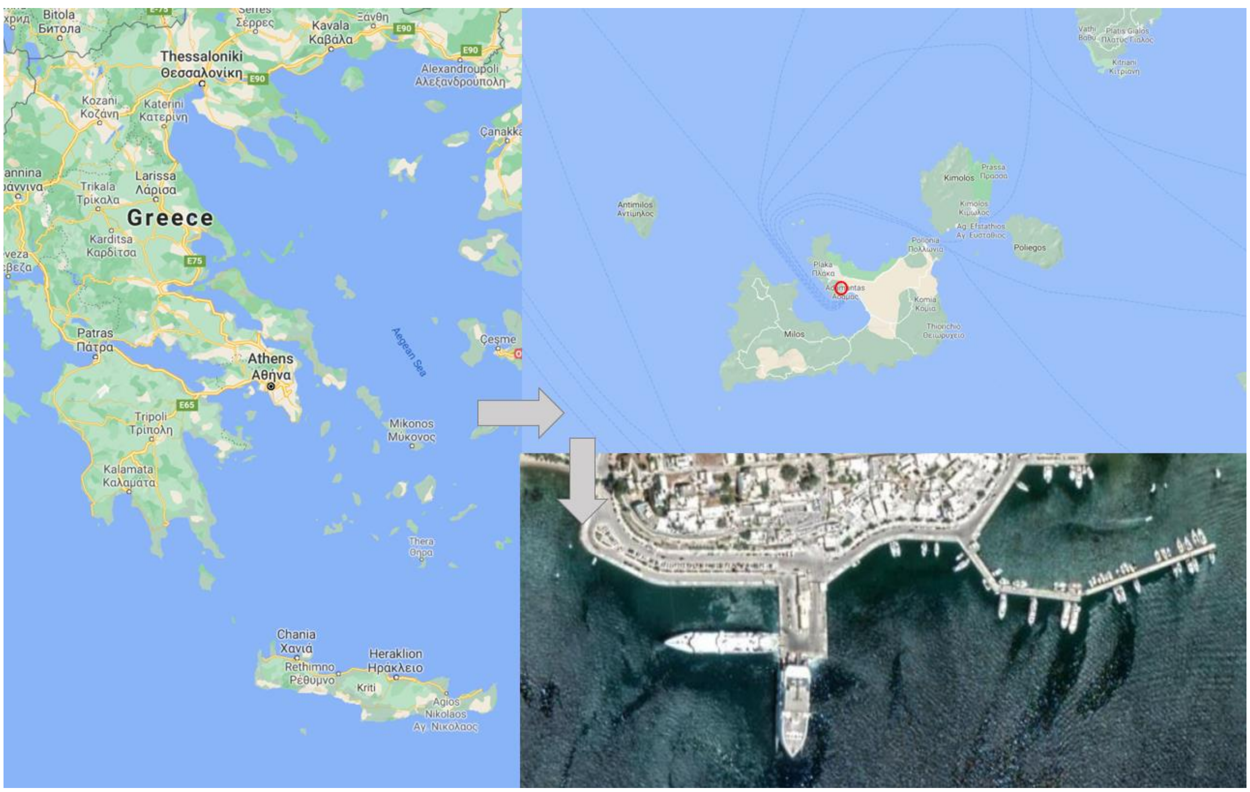

Figure 5.41. The geographical location of the Milos port

The next step was collecting the energy consumption data regarding the port's operations to establish its energy profile. After ensuring the local port authorities and the Hellenic Electricity Distribution Network Operator's collaboration, the research team acquired the needed data using a smart metering system. Average load equals 8.03 kW, peak load equals 37.85 kW, and average daily consumption equals 192.7 kWh/d (Figure 5.42). Based on the Greek market data, the equipment types to be used were set, and their actual cost was specified. Afterwards, the island's energy mix was calculated using the local energy supplier's data and the Technical Chamber of Greece's annual reports.

The probability of implementing the cold ironing technology in a small port is challenging, as no significant research has been conducted yet. It is crucial to design the ports' energy profile to implement the CI technology properly. The energy profile corresponds to the energy demand met by the berthing ships' auxiliary engines' operation during berthing time. The information was obtained by the local port police and the agents of each shipping company. Then, MATLAB software was utilised to distribute the hourly energy consumption throughout the year. Specifically, by examining every hour, day, and month, an individual energy profile was created for each ship. The total ships' energy profile is equal to their sum. Average load equals 67.02 kWh/d, peak load equals 1,035 kW, and average daily consumption equals 1,608.4 kWh/d (Figure 5.43). Table 5.8 presents the energy data for the port's and ships' energy profile.

Table 5.8. Energy data for the port's and vessels' energy profile

Energy profile	Port	Ships
Average load (kW)	8.03	67.02
Peak load (kW)	37.85	1,035
Average daily consumption (kWh/d)	192.7	1,608.4

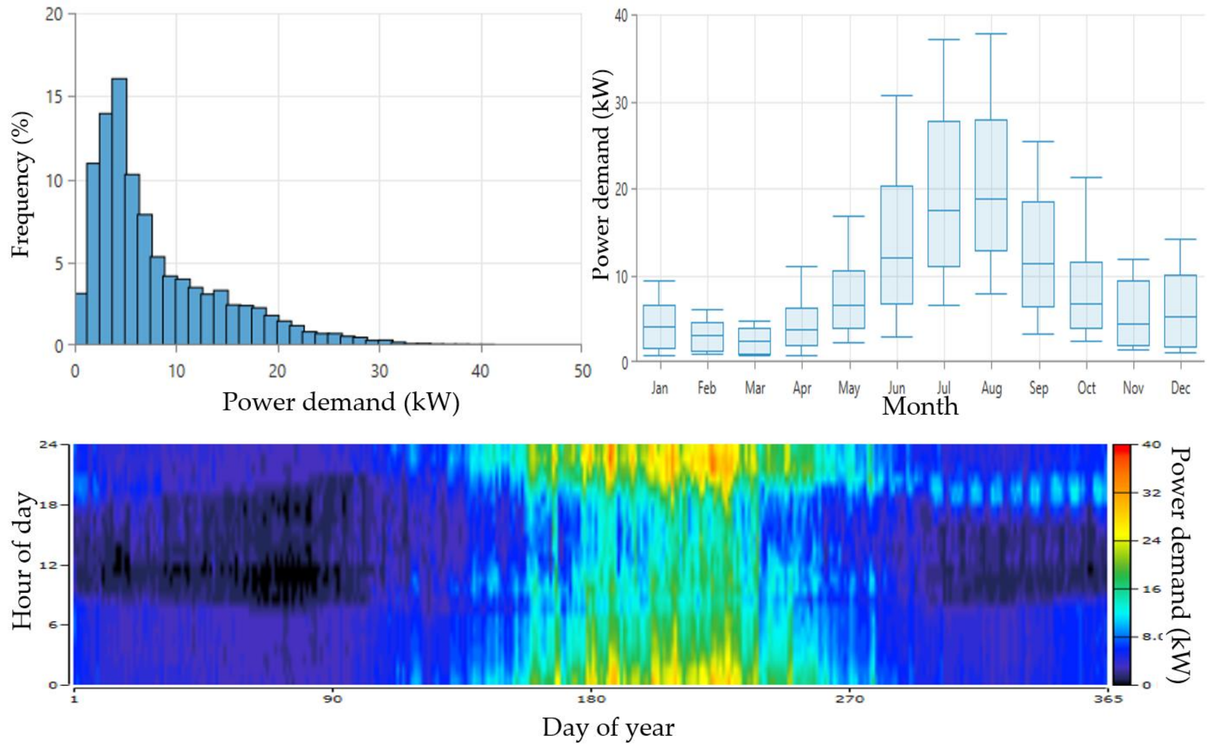

Figure 5.42. Annual energy profile for the Adamas' port

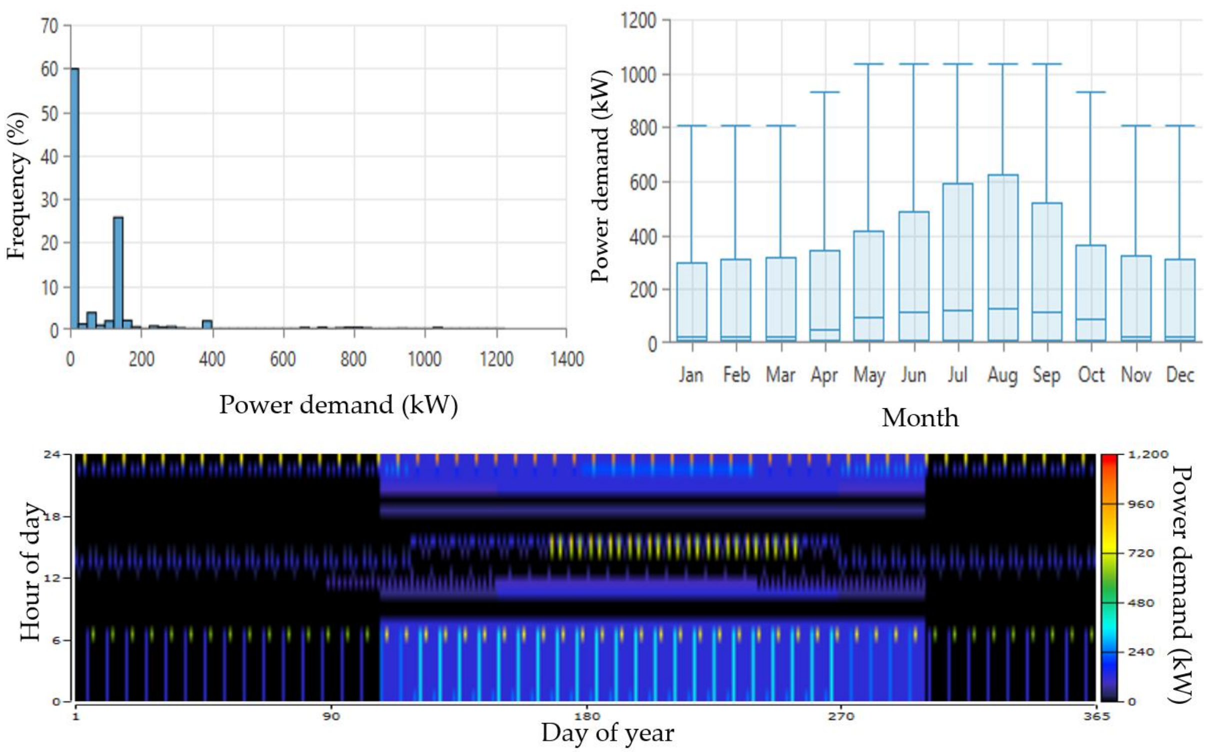

Figure 5.43. Annual energy profile for the berthed ships

Despite being located in an area, with a lot of sunny days throughout the year (Figure 5.44) and constant (but not extreme) winds (Figure 5.45), there is no generation based on RES yet. Thus, the whole port's energy needs are covered by the local electricity supplier.

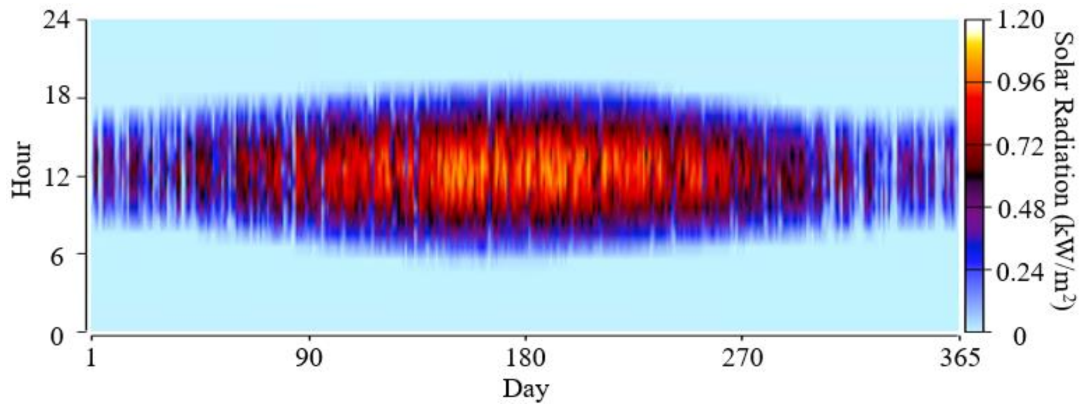

Figure 5.44. Adamas' port hourly solar potential

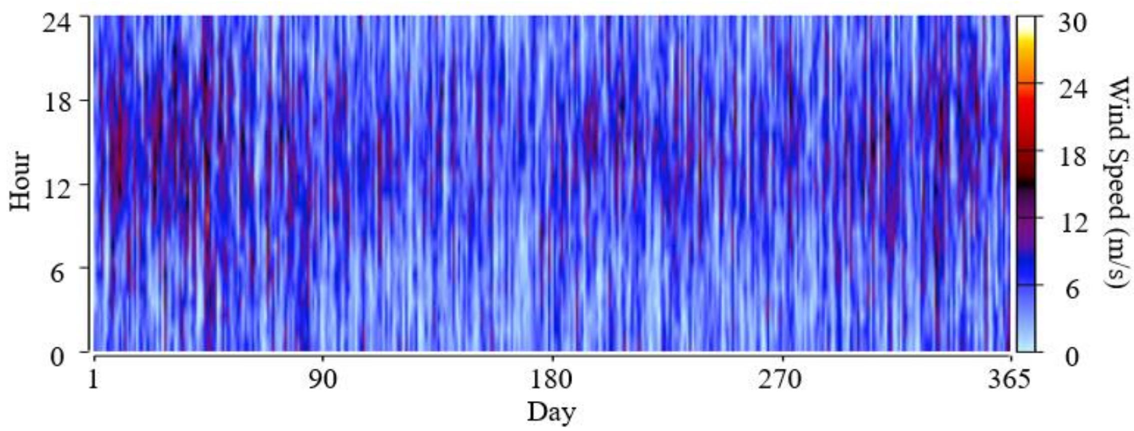

Figure 5.45. Case study's hourly wind potential

5.3.2 Cold-ironing and hydrogen integration methodology

This part aims to examine different methods capable of upgrading the small-sized port of Adamas in Milos Island. Hydrogen systems have never been examined for such small case studies before, as far as the research team is concerned. Actual data were used regarding the energy profile, the GHGs calculation, and the incorporated technologies to enhance the outcomes' reliability. Specifically, the prospect of embedding a green hydrogen system in a port is examined in terms of autonomy and minimisation of GHG emissions. Furthermore, the cold-ironing technology is integrated and examined to eliminate berthing ships' emissions in a small port for the first time, according to the recent EU legislation. Finally, the proposed system's sustainability is evaluated regarding its economic viability, social acceptance, and the reduction/minimisation of the environmental footprint.

5.3.2.1 Case study selection

According to a previously-created typology, the selected case study is the small-sized port of Adamas in Milos Island. The port serves the island's inhabitants' needs, providing ferry transport to the mainland or other islands, such as Piraeus, Rethymno, Heraklion, and Syros.

5.3.2.2 Data collection

The next step was collecting the energy consumption data regarding the port's operations to establish its energy profile. After ensuring the local port authorities' and the Hellenic Electricity Distribution Network Operator's collaboration, the research team acquired the needed data using a smart metering system.

Based on the Greek market data, the equipment types to be used were set, and their actual cost was specified. Afterward, the island's energy mix was calculated using the local energy supplier's data and the Technical Chamber of Greece's annual reports.

The probability of implementing CI technology in a small port is challenging, as there is not enough scientific evidence to support it. To implement the CI technology, it is crucial to design the ports' energy profile. To format it, the energy demand of ships' auxiliary diesel engines, while at berth, is needed, as well as the berthing time. This information was obtained by the local port police and the agents of each shipping company.

5.3.2.3 Examined technologies description and mathematical modeling

Considering the available Greek market data, the selected photovoltaic (PV) panel was the SunPower X21-335-BLK (Table 5.9) due to its availability and cost-effectiveness. The cost data varies according to the installed operation power, and certain costs per power determine the variance.

Table 5.9. Technical characteristics and cost data of SunPower X21-335-BLK

Power per panel (kWp)	Optimal operating temperature	Efficiency (%)	Lifetime (y)	Power (kWp)	Initial Capital (€)	Replacement cost (€)	O&M cost (€/y)
0.335	43	21	25	1	1,400	1,400	10
				10	9,000	11,000	100
				50	40,000	45,000	500
				100	75,000	85,000	1,000
				500	350,000	400,000	5,000
				1,000	600,000	700,000	10,000

The hourly power generation capacity for the solar PV module is calculated by Equation 46 [376].

$$P_{PV} = Y_{PV} \times f_{PV} \times \frac{I_T}{I_S} \times [1 + a \times (T_{cell} - T_S)(46)$$

Y_{PV} is the PV's rated capacity, f_{PV} is the derating ratio, I_T is the incident irradiation, I_S is the standard test irradiation, α is the temperature coefficient, T_{Cell} is the cell's temperature, and T_S is the temperature at standard test condition.

The total radiation for the solar PV is calculated from Equation 47 [377].

$$I_{ts} = I_{bs} \times R_{sh,s} + I_{ds} \times R_{ds} + (I_{bs} + I_{ds}) \times R_{rs} \ (47)$$

I_{bs} is the normal irradiation from the sun, R_{sh}, s is the sun's shunt resistance, I_{ds} is diffuse solar irradiation of the PV, R_{ds} is the diffuse tilt factor R_{rs} is the tilt factor for the reflected solar irradiations. The solar PV maximum output power is calculated from Equation 48 [377].

$$P_{ARR} = N_{Ss} \times N_{Ps} \times P_{Ms} (48)$$

N_{Ss} are the in-series connected solar PV modules, NPs are the connected solar PV modules in shunt, and PMs are the solar PV power output.

Considering the available Greek market data, the chosen wind turbine (WT) was the Aeolos H-10kW (Table 5.10). The cost data varies according to the number of pieces installed, and certain costs per power determine the variance.

Table 5.10. Technical characteristics and cost variance per installed piece for Aeolos H10kW

Technical characteristics	Nominal power (kW)	10
	Peak power (kW)	11
	Minimum sufficient wind speed (m/s)	2.50
	Nominal wind speed (m/s)	10
	Lifetime (y)	20
	Efficiency (%)	95
Cost Variance	Initial capital per piece (€)	35,000
	Replacement cost per piece (€)	40,000
	O&M per piece (€/y)	500
	Initial capital per 5 pieces (€)	150,000
	Replacement cost per 5 pieces (€)	150,000
	O&M per 5 pieces (€/y)	500

Wind speed, according to the hub height, is calculated from Equation 49 [377].

$$U_s = U_i \times \left[\frac{h}{h_i}\right]^x (49)$$

U_s is the wind's speed at a height h, U_i is the wind's speed at a height h_i, and x is a power law.

The mechanical output power of a WT is calculated from Equation 50 [377].

$$P_m = C_P(\lambda, \beta) \times \frac{\rho \times A}{2} \times U_W{}^3 (50)$$

where P_m is WT's mechanical power output, C_p is the performance coefficient, λ is a tip-speed ratio of a rotor blade, β is a pitch blade angle in degrees, ϱ is the air's density, A is the WT's swept area, and U_W is the wind's speed.

The WT's output power is calculated from Equation 51 [378].

$$P_{WT}(t) = \begin{cases} 0,\ U_W \leq U_{cut-in}\ or\ U_W \geq U_{cut-out} \\ P_r \cdot \left(\frac{{U_W}^3 - {U_{cut-in}}^3}{{U_r}^3 - {U_{cut-in}}^3}\right), U_{cut-in} < U_W \leq U_r \\ P_r\ , U_r < U_W \leq U_{cut-out} \end{cases} \quad (51)$$

where U_r is the nominal speed, $U_{cut\text{-}in}$ is the cut-in speed, $U_{cut\text{-}out}$ is the cut-out speed, and P_r is the output power at rated speed

As previously mentioned, investments involving CI equipment are still immature when investigating medium and (especially) small-sized ports, so international literature was consulted to estimate the potential cost. According to research by C. Trozzi et al., in Napoli's cruise terminal (15.5 MW average power), the total cost for decentralised dock systems, with portable alternative marine power, is approximately equal to 20,000€ [379]. The port of Adamas cannot accommodate more than three vessels simultaneously, so the assumption is set to 3 dock systems. Summing a 25% error factor, the total cost for implementing CI technology in Adamas' port was calculated to be 75,000€.

The hydrogen system consists of an FC, an El, and an HT [380]. According to the national literature, the initial cost data comes from the Greek market, but due to the extremely high values, market data, according to the national literature, was also utilised. Table 5.11 presents the hydrogen's equipment cost, according to the Greek and the investigated literature market data.

Table 5.11. Market data for the hydrogen equipment's cost

Component	Market Data	Capital cost (€)	Replacement cost (€)	O&M cost (€/year)	Lifetime (y)
El	Greek	20,000/kW	20,000/kW	0	25
	Literature	2,000/kW	2,000/kW	0	25
HT	Greek	12,195/kg H_2	12,195/kg H_2	0	25
	Literature	1,500/kg H_2	1,500/kg H_2	0	25
FC	Greek	4,500/kW	4,500/kW	0	4.57
	Literature	2,500/kW	2,500/kW	0	4.57

The El's output power is calculated from Equation 52 [381].

$$P_{El-Tank} = P_{Ren-El} \times \eta_{El} \ (52)$$

where P_{Ren-EL} is the input power of the El and η_{EL} is the efficiency of it.

The HT's stored energy is calculated from Equation 53 [381].

$$E_{Tank(t)} = E_{Tank(t-1)} + (P_{El-Tank} \times \Delta t) - \left(P_{Tank-FC} \times \Delta t \text{ x } \eta_{storage}\right) \ (53)$$

Δt is the length of the time step, and ηstorage is the efficiency of the hydrogen storage system.

The stored hydrogen's volume is calculated from Equation 54 [381].

$$M_{HT} = \frac{E_{Tank(t)}}{HHV_{H_2}} \ (54)$$

where HHV_{H2} is the heat value of the hydrogen.

The FC's output voltage is calculated from Equation 55 [381].

$$V_{FC} = N_{cell} \times E_{cell} = E - V_{act} - V_{ohm} - V_{con} \ (55)$$

where V_{FC} *is the* output voltage, E *is the* open-circuit voltage, V_{act} *is* activation over-voltage, V_{ohm} is ohmic over-voltage and V_{con} is concentration over voltage.

One vital part of this study was calculating the case study's energy mix to quantify its EF. As previously mentioned, there is currently no energy generation in the port, and the local factory of electricity covers the entirety of energy needs. To calculate the energy mix for the case study, the Technical Chamber of Greece and the local factory's authorities were consulted:

- To convert the energy needed to primary produced electric energy, a multiplication with 2.9 kWh is needed. Also, for every produced kWh of electric energy by conventional fossil fuels-burning engines, 0.989 kg CO_2e are emitted to the atmosphere [382]
- The island's energy mix consists of a diesel generator (24.93% energy production), a mazut generator (62.34% energy production), and RES (12.73% energy production).

In conclusion, the emissions factor used to calculate the EF for the port's energy needs is calculated by Equation 56:

$$\mathrm{EF} = (24.93\% + 62.34\%) \times 0.989\frac{\mathrm{kgCO_2 - e}}{\mathrm{kWh}} + 12.73\% \times 0 \Rightarrow \mathrm{EF} = 0.8631\frac{\mathrm{kgCO_2 - e}}{\mathrm{kWh}} \quad (56)$$

The proposed system's cost is calculated from each component's sum. Specifically, the added costs concern the PVs, the WTs, the CI technology, the FC, the El, and the HT. Equation 57 presents the total system's cost.

$$C_{total} = C_{PV} + C_{WT} + C_{CI} + C_{FC} + C_{El} + C_{HT} \quad (57)$$

C_{PV} is the PV's cost; C_{WT} is the WT's cost, C_{CI} is the CI technology's cost, C_{FC} is the FC's cost, C_{El} is the El and C_{HT} is the HT's cost.

Each of these costs is calculated from Equation 58.

$$C_i = N_i \times \left[C_{Cap,i} + \left(C_{Rep,i} + N_{r,i}\right) + C_{OM,i}\right] \quad (58)$$

where N_i is each component's number in the system, $C_{Cap,i}$ is each component's initial capital (IC) cost, $C_{Rep,i}$ is component's replacement cost, $N_{r,i}$ is each component's replacement number, and $C_{OM,i}$ is each component for operation and maintenance.

The system's Levelised Cost of Energy (LCOE) is calculated from Equation 59 [383].

$$LCOE = \frac{C_{ann,tot} - c_{boiler} \times H_{served}}{E_{served}} \quad (59)$$

$C_{ann, tot}$ is the total annualised cost of the system, c_{boiler} is the boiler's marginal cost, H_{served} is the total thermal load served, and E_{served} is the total served electrical load.

5.3.2.4 Scenarios' conceptualisation

To find the optimal solution for the Adamas' port, either with or without taking the ship's energy profile into account, several scenarios were conceptualised and simulated using the Homer PRO tool. The first scenario (base scenario) represents the current port's state. The following six scenarios (2-7) aim to provide the optimal solution without considering the ships' energy load (CI), while the last six scenarios (8-13) have the same design as scenarios 2-7, while including the CI technology. The other embedded sensitivity cases were the hydrogen system's cost source (Greek or literature market data), the time needed to fill the HT (24h or 8h), and the utilised RES (PV or PV+WT) (Table 5.12).

Table 5.12. Design parameters for each scenario

Scenario	Source of cost (market data)	HT's fill time (h)	Designing load demand	CI	RES
1	×	×	×	×	×
2	Greek	24	Mean	×	PV
3	Greek	24	Mean	×	PV+WT
4	Literature	24	Mean	×	PV
5	Literature	24	Mean	×	PV+WT
6	Literature	24	Peak	×	PV
7	Literature	8	Mean	×	PV
8	Greek	24	Mean	✓	PV
9	Greek	24	Mean	✓	PV+WT
10	Literature	24	Mean	✓	PV
11	Literature	24	Mean	✓	PV+WT
12	Literature	24	Peak	✓	PV
13	Literature	8	Mean	✓	PV

5.3.3 Outcomes of the cold-ironing and the hydrogen storage system integration

5.3.3.1 General results

A thorough techno-economic analysis of the proposed HRES with and without incorporating the CI technology for the on-shore power supply of ships, is presented based on the actual port's energy profile. Also, the actual market data of the components' costs are implemented. The components of each scenario's system are presented in Table 5.13. The major study's outcomes are presented in Table 5.14 and Table 5.15. Table 5.14 presents the implementation or not of the CI technology for each scenario, as well as the sizing of each proposed component, and the portion of each energy generation technology. In contrast, Table 5.15 shows each scenario's system's cost, the simple payback period (PP), the efficiency in economic terms, the HRES autonomy (in hours), and the EF for each simulated scenario's HRES (without taking into consideration the LCA of each component). In the case of CI, the berthed ships' actual load is taken into consideration, leading to increased energy demand for the port's services.

Table 5.13. The components of each conceptualised scenario's system

Non-CI cases						CI cases					
Scenario	PV	WT	HESS	EL	FT	Scenario	PV	WT	HESS	EL	FT
1	×	×	×	×	×	8	×	×	✓	×	×
2	✓	×	✓	Mean	24-h	9	✓	×	✓	Mean	24-h
3	✓	✓	✓	Mean	24-h	10	✓	✓	✓	Mean	24-h
4	✓	×	✓	Mean	24-h	11	✓	×	✓	Mean	24-h
5	✓	✓	✓	Mean	24-h	12	✓	✓	✓	Mean	24-h
6	✓	×	✓	Peak	24-h	13	✓	×	✓	Peak	8-h
7	✓	×	✓	Mean	8-h						

As mentioned before, in the methodology section, the first scenario's system presents the current port state (baseline). There is no energy generation on-site for the port's needs; the port is depended, in energy terms, on the local electricity grid. The two subsections of the table represent the different CI scenarios and the comparisons between the systems of scenarios 2 to 7, and these of scenarios 8 to 13. Two optimal systems were picked, with or without the CI implementation.

Table 5.14. Technical characteristics of each system's components per scenario

		RES		Hydrogen system			Energy generation			
Scenario	CI	PV (kW)	WT (kW)	El (kW)	FC kW)	HT (kg)	Grid (%)	PV (%)	WT (%)	FC (%)
1	×	0	0	0	0	0	100	0	0	0
2	×	46.1	0	15	8	7	24.5	63.5	0	12
3	×	30.8	1	15	8	7	23.4	46.2	21	9.4
4	×	48.4	0	15	8	7	19.4	64.6	0	16
5	×	32.2	1	15	8	7	18,9	47.3	20.5	13.3
6	×	44.5	0	45	40	7	30,2	62.6	0	7.2
7	×	50.7	0	45	8	7	14,5	65.6	0	19.9
8	✓	437	0	130	80	65	28.4	59.5	0	12.1
9	✓	424	1	130	80	65	28.0	58.0	1.9	12.1
10	✓	438	0	130	80	65	28.4	59.5	0	12.1
11	✓	425	1	130	80	65	27.9	58.0	1.9	12.1
12	✓	456	0	130	1075	65	24.0	60.5	0	15.5
13	✓	461	0	390	80	65	23.1	60.8	0	16.1

The impact from the port's operation is economic, social (leading to instability, in extreme energy demand events, or blackouts in the local power plant), and environmental (the local factory generates electricity by fossil fuels' combustion). Thus, the impact is also economic and environmental, leading to significant benefits for the port in both sectors. The economic and the environmental characteristics of each scenario's proposed system are presented in Table 5.15.

The systems of scenarios 2, 3, 6, 8, 9, and 12 are economically infeasible due to the increased LCOE, which is higher than the baseline LCOE. Indicatively, the LCOE is doubled compared to the baseline one, leading to unprofitable investments as the systems' PP, ROI, and IRR are indicating.

Table 5.15. Economic and environmental characteristics of each system per scenario

Scenario	System's cost				Economic efficiency			Autonomy (h)	CF ($kgCO_{2,e}$)
	NPC (€)	LCOE (€/kWh)	O&M (€)	IC (k€)	PP (y)	ROI (%)	IRR (%)		
1	145,544	0.160	11,258	0	-	-	-	-	176,123.6
2	470,133	0.356	908	458.4	-	-	-	29.0	0
3	496,975	0.387	1,196	481.5	-	-	-	29.0	0
4	117,309	**0.094**	1,398	99.2	**9.2**	**5.9**	**8.8**	29.0	0
5	144,711	0.120	1,782	121.7	11.7	3.8	6.0	29.0	0
6	248,717	0.220	536.4	241.8	22.6	0.4	0.8	29.0	282.8
7	185,015	0.158	1,861	161.0	16.8	1.8	3.1	29.0	2.5
8	4,242,942	0.318	8,376	4,134.7	-	-1.9	-	28,9	255.3
9	4,279,084	0.323	9,167	4,160,6	-	-1.6	-	28.9	0
10	1,028,255	**0.077**	6,855	939.6	**8.6**	**7.4**	**10.5**	28.9	0
11	1,064,969	0.080	7,664	965.9	8.9	7.0	10.0	28.9	0
12	3,498,959	0.276	4,563	3,440.0	-	-1.0	-	28.9	0
13	1,611,478	0.128	10,507	1,475.6	13.9	2.8	4.5	28.9	0

Regarding the port's environmental impact, the systems of scenarios 6, 7, and 8 are not environmentally friendly due to their increased CF. The positive CF indicates that the generated energy from the HRES is not adequate to cover the port's needs, so the grid energy is needed. The CF index represents the grid purchases as the components' LCA CF is not considered for this study. Indicatively, the CF indexes for the hydrogen storage system is 6.5g$CO_{2,eq}$/kWh, while the corresponding CF indexes for PVs and WTs are 37.3 and 40g$CO_{2,e}$/kWh.

5.3.3.2 Grid-connected HRES without the CI implementation

A total number of 6 scenarios were conceptualised and simulated regarding the optimal sizing of the proposed HRES without implementing the CI technology. The optimum HRES based on the system's LCOE and CF for each scenario was placed into a candidate pool; the best scenario from the pool of optimum solutions was chosen as the ideal. The selected-optimal HRES were chosen based on three particular criteria: the suggested HRES LCOE is the first. The port's operational dependability and stability insurance is the second criterion, while the CF is the third. Ports are responsible for ensuring that their services are delivered without interruption, regardless of possible electricity grid's outages.

Consequently, the research team designed and sized the hydrogen storage system to provide at least 28-h autonomy to the port services. Only if the recommended HRES's CF is zero is the lowest-NPC scenario picked as ideal. The LCOE and CF per candidate scenario are presented in Figure 5.46.

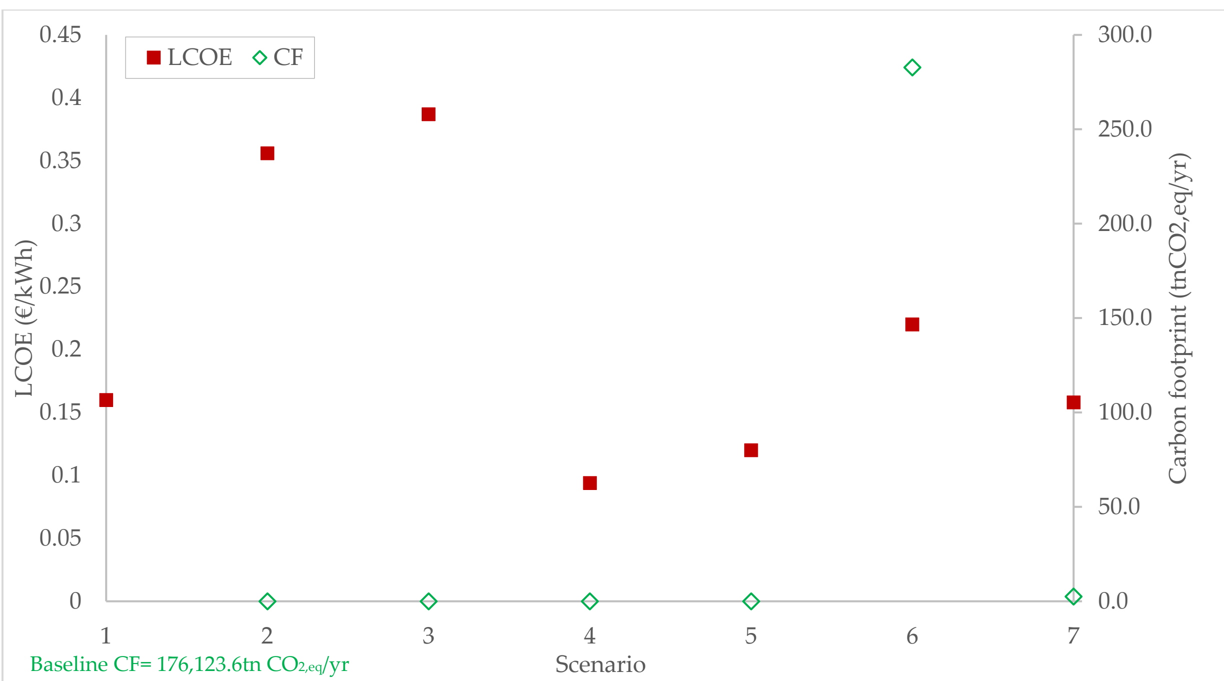

Figure 5.46. LCOE and CF of the optimal solutions per scenario (1-7) for the non-CI cases

The initial LCOE is 0.16€/kWh, and the initial CF is 176,123,6tn$CO_{2,eq}$/yr according to Figure 5.46. The economically infeasible scenarios are those with higher LCOE than the baseline (2, 3, and 6), while the LCOE of the system of scenario 7 is near the baseline value; all these four scenarios are eliminated. Only the systems of scenarios 4 and 5 are picked as optimal, and the best among the two has to be picked.

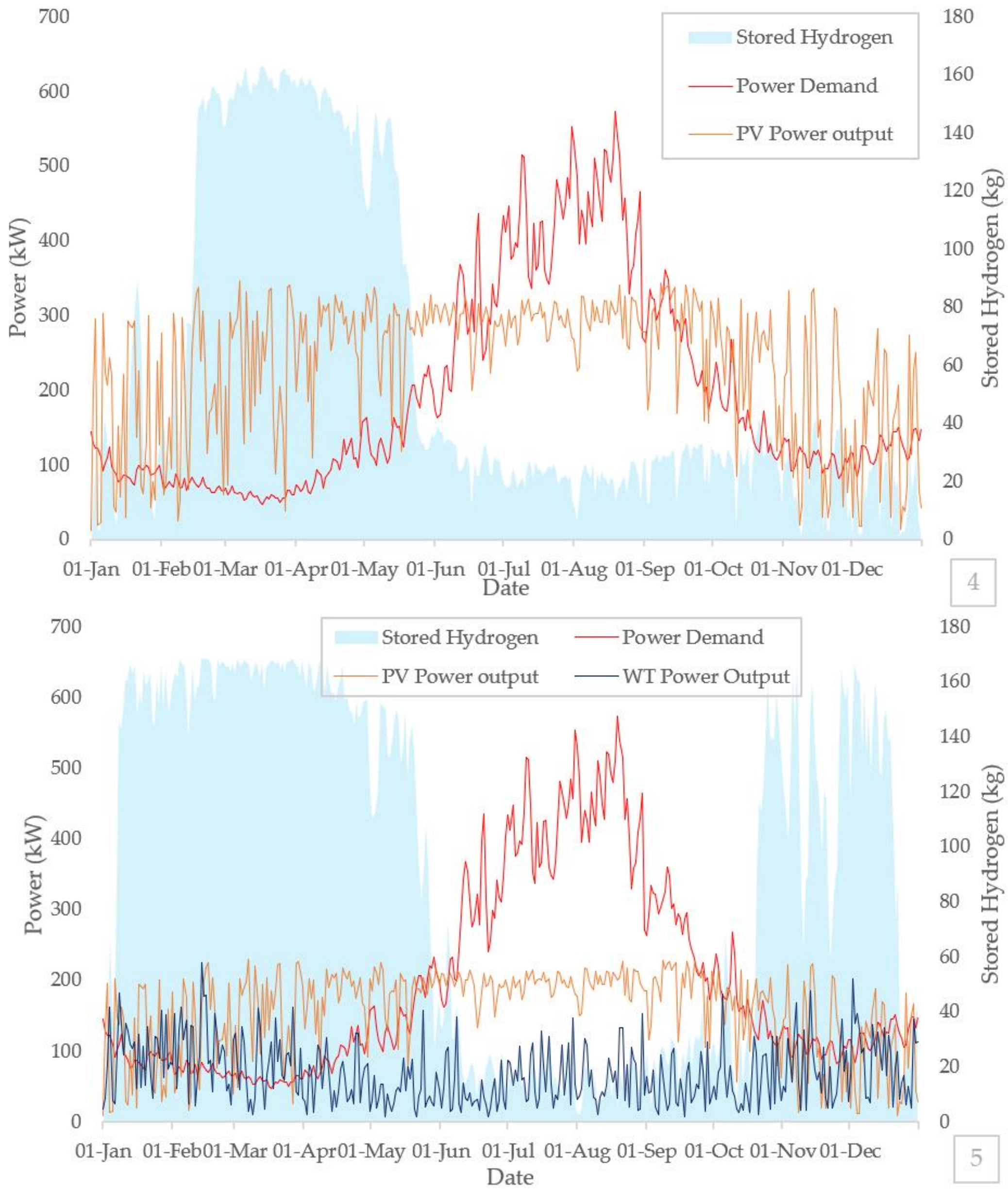

Figure 5.47. Energy generation scheme for the two optimum scenarios for the non-CI cases

The comparison between the systems of the two optimal scenarios was made regarding their LCOE, their CF and their social acceptance. The CF of both systems equals zero, meaning that the energy generated by the RES and stored in the HESS is adequate to cover the port's energy needs in cooperation with the NM functionality. Although, the social acceptance of the system's components of scenario 5 is less than this of scenario 4 due to the implementation of 1 WT, which is well-known to be not accepted by the public. Moreover, the system's LCOE of scenario 4 is less than this of scenario 5; 0.094€/kWh compared to 0.120€/kWh, respectively. Figure 5.47 represents the daily energy generation for each scenario's system.

The benefits of building a PV park are demonstrated by the consistent PVs' energy output throughout the year, demonstrating the case study's significant solar potential. The PVs' energy output peaks during the noon hours, and extra energy is created throughout the year. Rather than immediately delivering it to the local electricity grid (net-metering), it is delivered to the El to store it properly in the hydrogen tank, enabling the later use of the extra "green" energy generated during the day to be used during the night.

In scenario 4, the PVs provide the required energy for the port's needs in cooperation with the hydrogen fuel cell system activated when the PV-generated energy is not adequate; grid purchases are avoided when possible (Figure 5.48). Even if there is only 1 WT in scenario 5, the contribution to the total energy generation is high; WTs generate more energy than PVs as they can operate during night hours if there are adequate wind resources. The hydrogen tank is being filled during the year when the energy demand is low; the RES generates more energy than needed, which is not dumped into the electricity grid but stored in the hydrogen tanks to be used later in the year. During the summer months, when the port's energy demand is high, the stored hydrogen is lower in the hydrogen tanks as the fuel cell provides the energy needed the RES can not generate that to cover the port's energy needs.

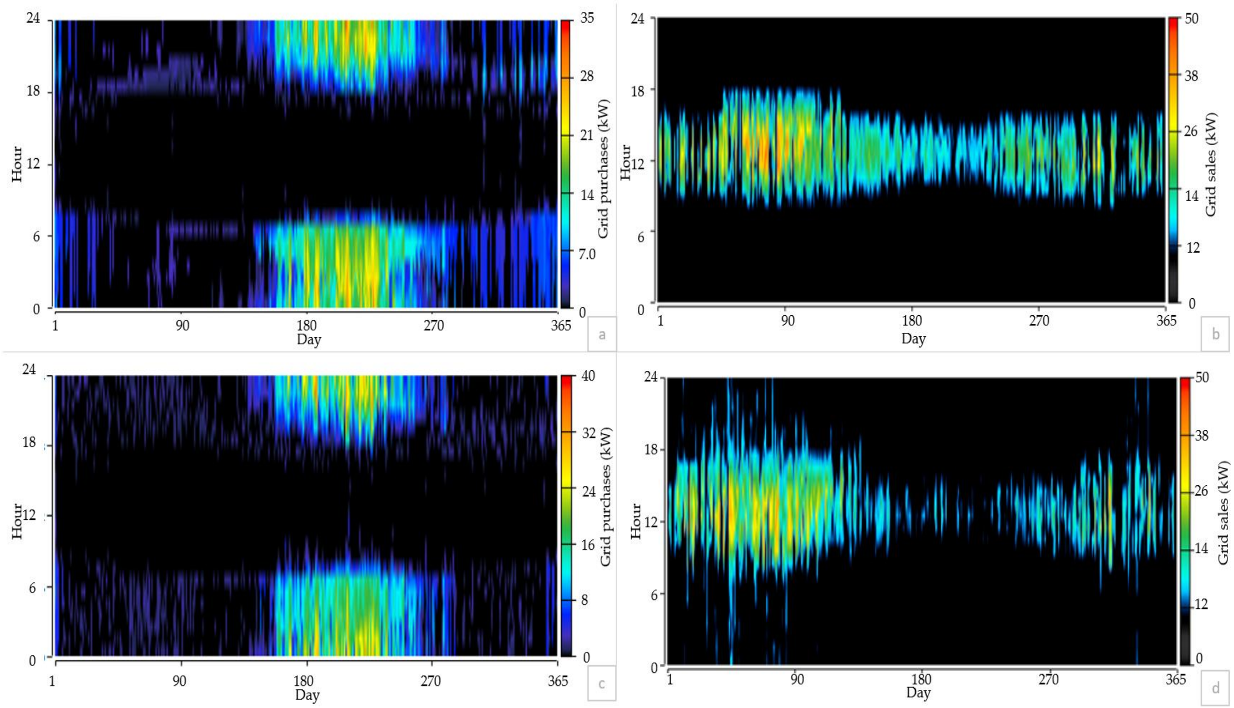

Figure 5.48. Grid purchases and sales for scenarios 4 (a, b) and 5 (c, d)

The grid purchases on scenario 5 are lower than on scenario 4 due to the implementation of the WT which can provide green energy during the night hours. On the other hand, through the NM function, the grid sales are higher for scenario 5 during the low-demand periods and lower during the higher-demand periods (summer).

5.3.3.3 Grid-connected HRES with the CI implementation

The CI technology implementation was created through the MATLAB software after obtaining the required data from the local port personnel and the ferries' companies. The exact ship routes were modeled through a smart integration algorithm created by the research team and converted the actual power of the vessels' engines to energy by considering their berth-time. Specifically, each ship arrives at the port on certain days and stay on-berth for a certain time according to its daily route; the calculation of its energy demand, if it would consume electricity instead of fossil fuels, is as accurate as possible. As a result, the energy demand for the ships is a lot greater than the port's actual demand; the port's energy profile has been increased accordingly (Figure 5.49).

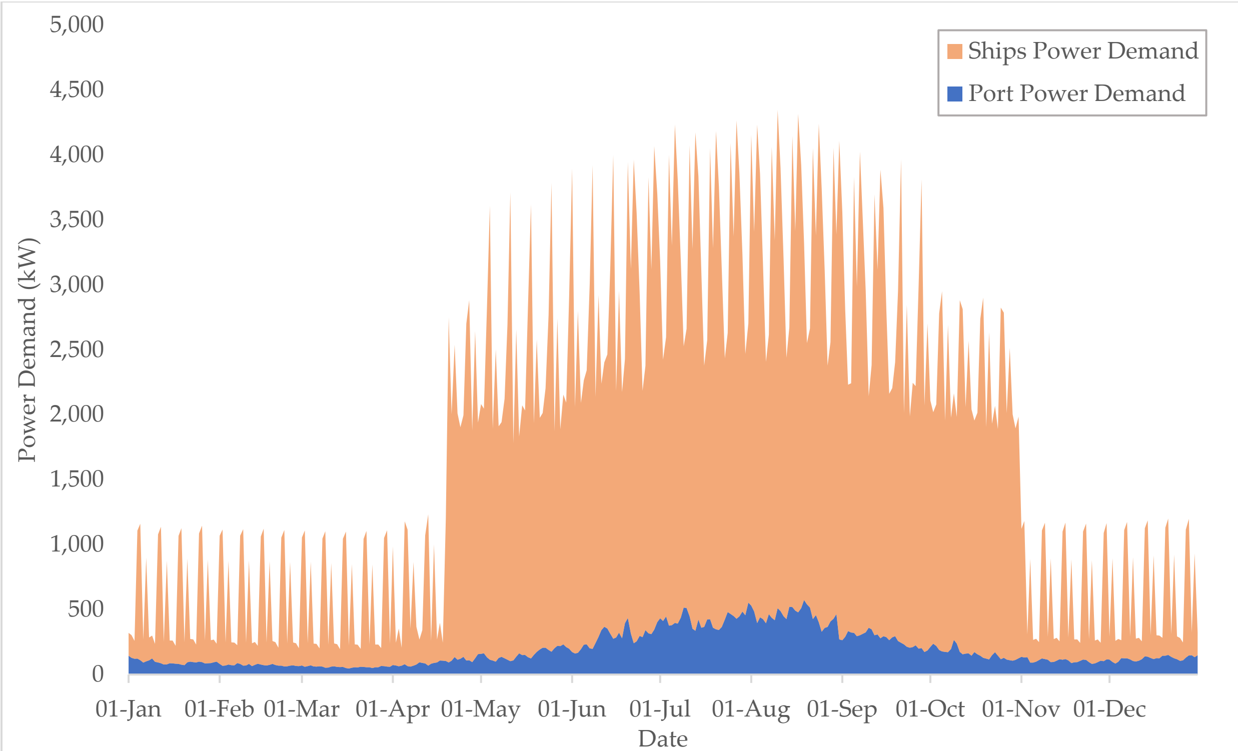

Figure 5.49. Port's energy profile for the CI cases

The port's energy demand is 657,497kWh/yr compared to 70,365kWh/yr, which was the energy demand on the baseline case (almost 10 times higher); the port, in this case, is handled as a medium-sized port according to the already mentioned typology.

The conceptualization of the scenarios is the same as in the previous case; Table 5.13 demonstrates the components of each scenario's system, while Table 5.14 and Table 5.15 present the technical and the economic/environmental characteristics of each scenario's system, respectively.

Figure 5.50 represents each scenario's system LCOE and CF. The CF of all the examined scenarios is zero except for the system of scenario 8, which is not capable of providing all the required energy to cover the port needs; grid purchases are higher than grid sales in this scenario.

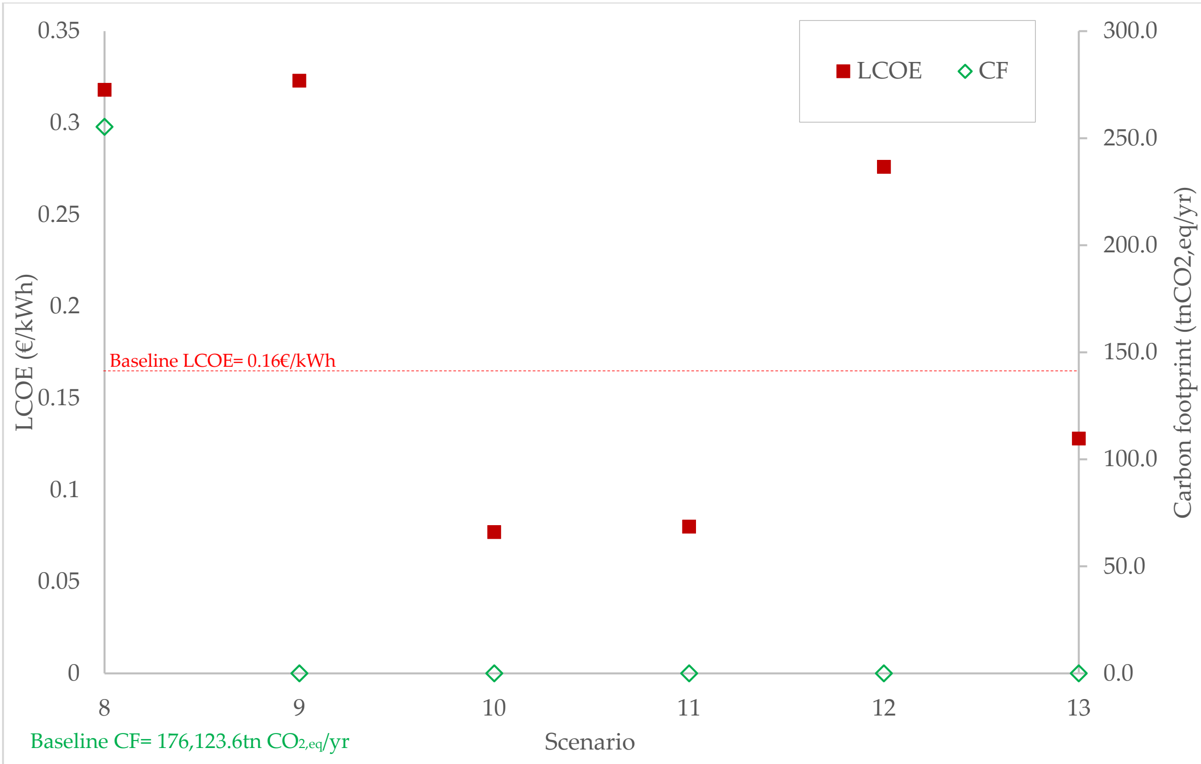

Figure 5.50. LCOE and CF of the optimal solutions per scenario (1-7) for the non-CI cases

The systems of scenarios 8, 9, and 12 have an LCOE higher than the baseline; they are economically infeasible, and their ROIs are negative meaning that the investments are not profitable and are not qualified to be picked in the candidate pool. The LCOE of the systems of scenarios 10, 11, and 13 have an LCOE lower than the baseline. These three scenarios have zero CFs; the grid sales are equal or higher than the grid purchases. The social criterion is fulfilled in scenarios 11, and 13 as there are no WTs. The other economical indexes (PP, ROI, IRR) are lower for scenario 13 than for scenario 11; the optimal system is this of scenario 11. For comparison reasons, the systems of scenarios 10 and 11 are compared; the energy generation schemes scenarios are presented in Figure 5.51.

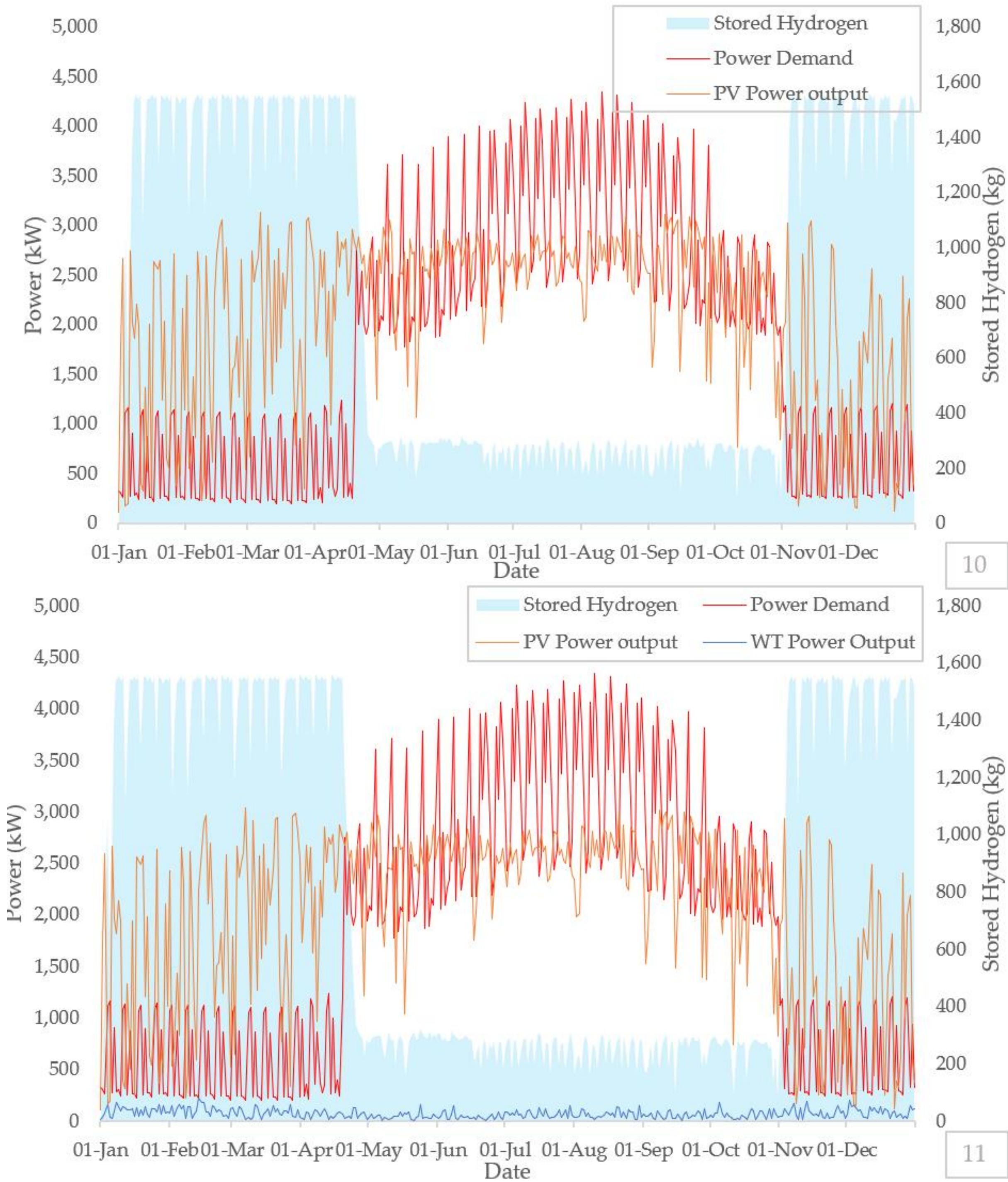

Figure 5.51. Energy generation scheme for the two optimum scenarios for the CI cases

In this case, the contribution of the implemented WT is scarce due to its low power output (10kW); due to the social acceptance criterion no more than one WT can be implemented near the port area. The PVs in collaboration with the FC are enough to provide the port with the required energy during the summer months (peak energy demand) for both cases. The hydrogen tank is filled during the winter months when the energy demand is low and there is excess energy from the RES. There is no noteworthy difference between the hydrogen tank levels among the two cases due to the high-RES penetration.

For the systems of scenarios 10 and 11, the grid purchases and sales are almost similar due to the low contribution to the energy generation by the installed WT in scenario 11. The system needs energy from the grid during the summer night-hours, as expected. The grid sales are higher during the winter day-hours as there is a lot of excess RES energy; as long as the hydrogen tank is full, the excess energy is transferred into the electricity grid to offset the grid purchases, utilizing the grid's grid NM functionality ().

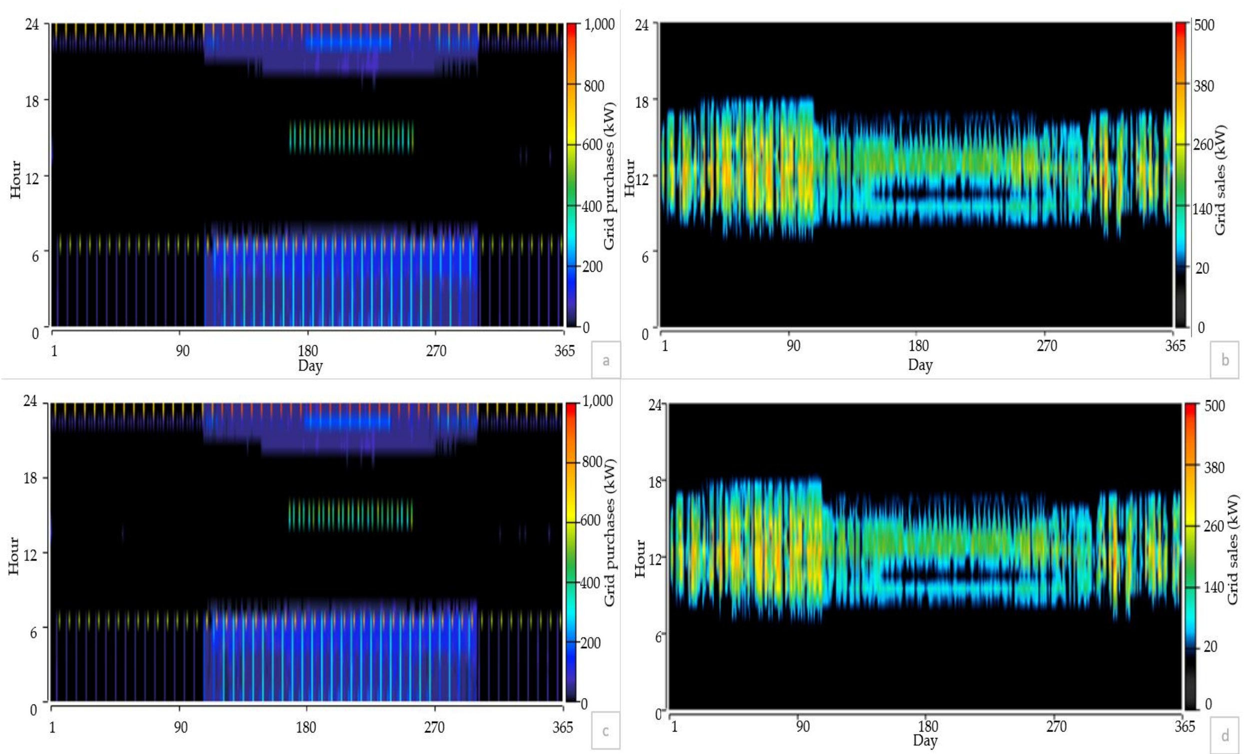

Figure 5.52. Grid purchases and sales for scenarios 10 (a, b) and 11 (c, d)

5.3.3.4 Comparison of the four optimal scenarios

The four optimal scenarios that were selected and moved into the candidate pool are compared all together in Figure 5.53. The RES generation is higher than the energy demand during the winter months (low demand periods), while the energy demand is higher than the RES generation during the summer months; grid energy is purchased to cover the port's energy needs. The contribution of the FC is higher during spring and summer when the stored hydrogen is converted into electricity to be used for the port's energy needs. The monthly grid purchases are scarce during the low-demand periods while they are increased during the high-peak seasons, as the HRES cannot provide the required energy to fully cover the port's needs.

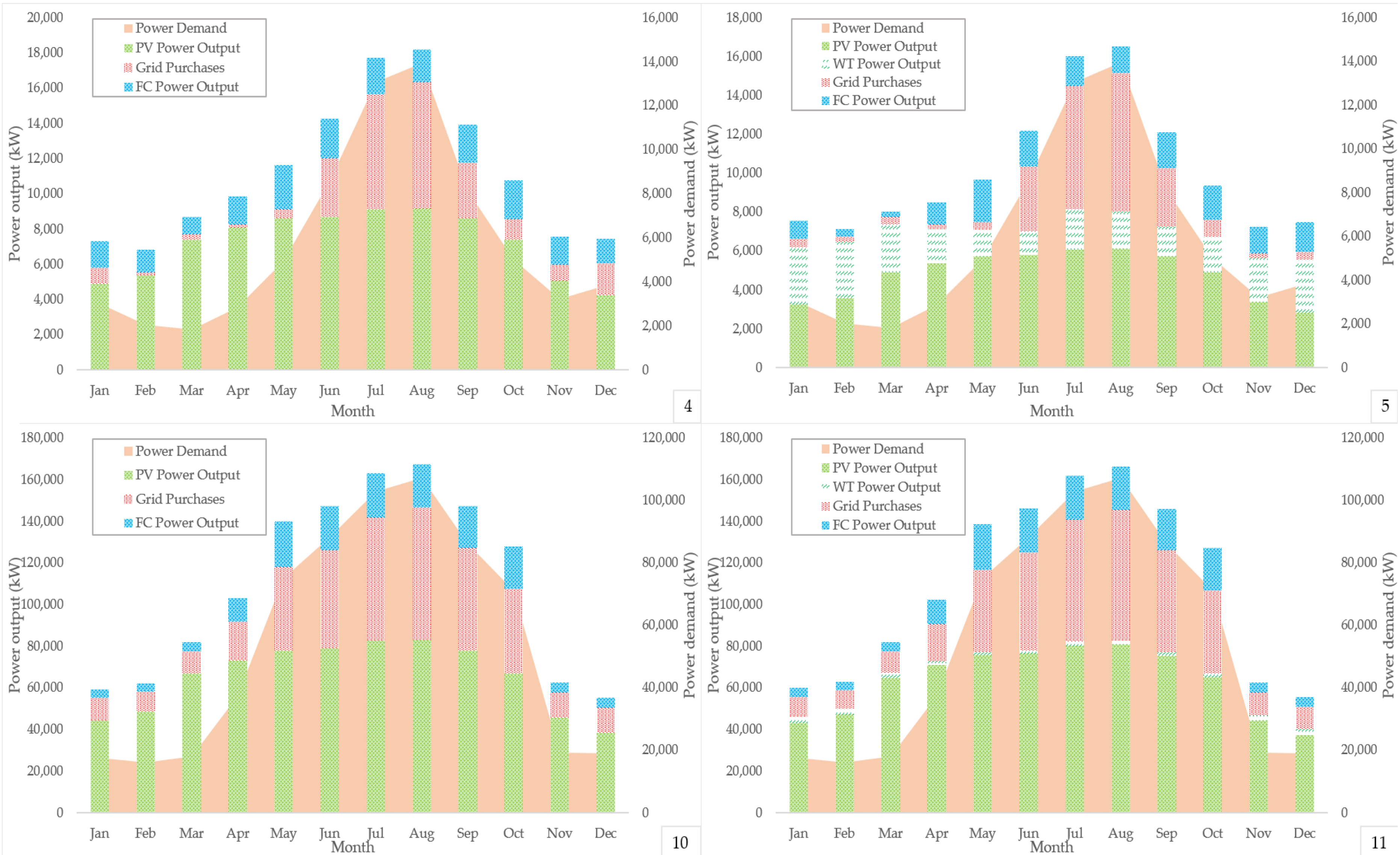

Figure 5.53. Monthly energy generation for the optimal scenarios

5.3.3.5 Sensitivity Analysis

To explore and analyse the impact of uncertainties on the recommended HRES, an LCOE sensitivity analysis was performed. Although the sensitivity analysis is carried out for all the ideal scenarios, only the best-selected for each CI case are presented. The LCOE of the HRES is affected by the cost of the HESS components, the solar radiation, wind speed, hours of autonomy, and typical daily energy use. As predicted, there is a significant influence on the overall HRES economic results, and any changes would influence the study's results. The impact is proportional to the change in the indices.

5.3.3.5.1 Sensitivity analysis on the non-CI cases

For the non-CI cases, the system of scenario 4 is the ideal both in terms of LCOE and CF; the social criterion is also satisfied as there are no WTs. In the event of an unanticipated increase in demand, the LCOE will rise because the suggested HRES will not meet the energy demands; nevertheless, the CF will be positive due to the grid purchases (Figure 5.54). In scenario 4, PV penetration is considerable, making the HRES extremely reliant on the area's solar potential. As a result, if solar radiation declines, the HRES will be unable to meet the overall energy demand, resulting in grid purchases and higher CF (Figure 5.54). Furthermore, losses in solar potential have a significant influence on the LCOE. Regarding the sensitivity analysis on the cost of the HESS components, the EL and the FC costs were examined, as shown in Figure 5.54. They both have a noteworthy impact on the system’s LCOE due to their high contribution on the initial capital as the most expensive components of the system; the FC has a slightly greater impact on the system’s LCOE due to its higher initial cost despite the almost half installed power compared to the EL.

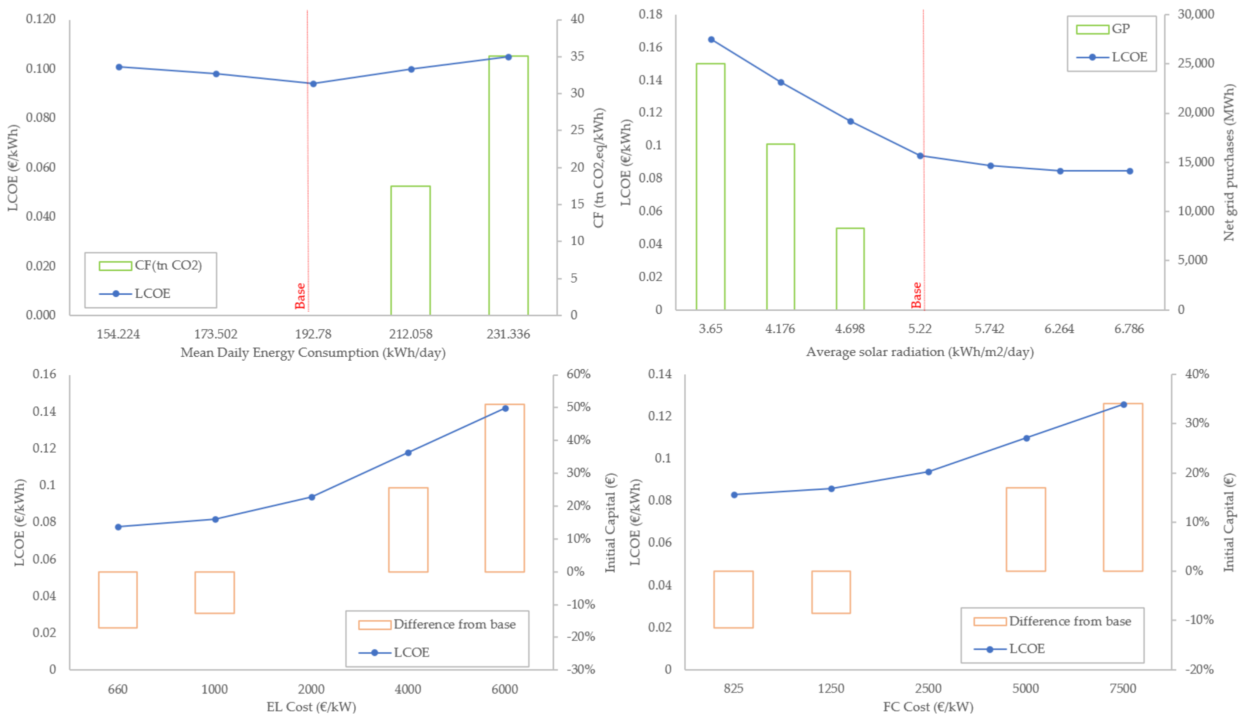

Figure 5.54. Sensitivity analysis for the four varying parameters for the non-CI cases

5.3.3.5.2 Sensitivity analysis on the CI cases

For the CI cases, the system of scenario 10 is the optimal regarding both the LCOE and the CF; the social acceptance is high as there are no WTs. The LCOE will rise in the event of an unexpected increase in demand since the recommended HRES will not be enough to fulfill the energy demands; nevertheless, the CF will be positive due to grid purchases (Figure 5.55). In scenario 10, PV penetration is high, making the HRES dependent on the solar potential of the location. As a result, if solar radiation falls below a certain threshold, the HRES will not fulfill total energy demand, resulting in grid purchases and increased CF (Figure 5.55).

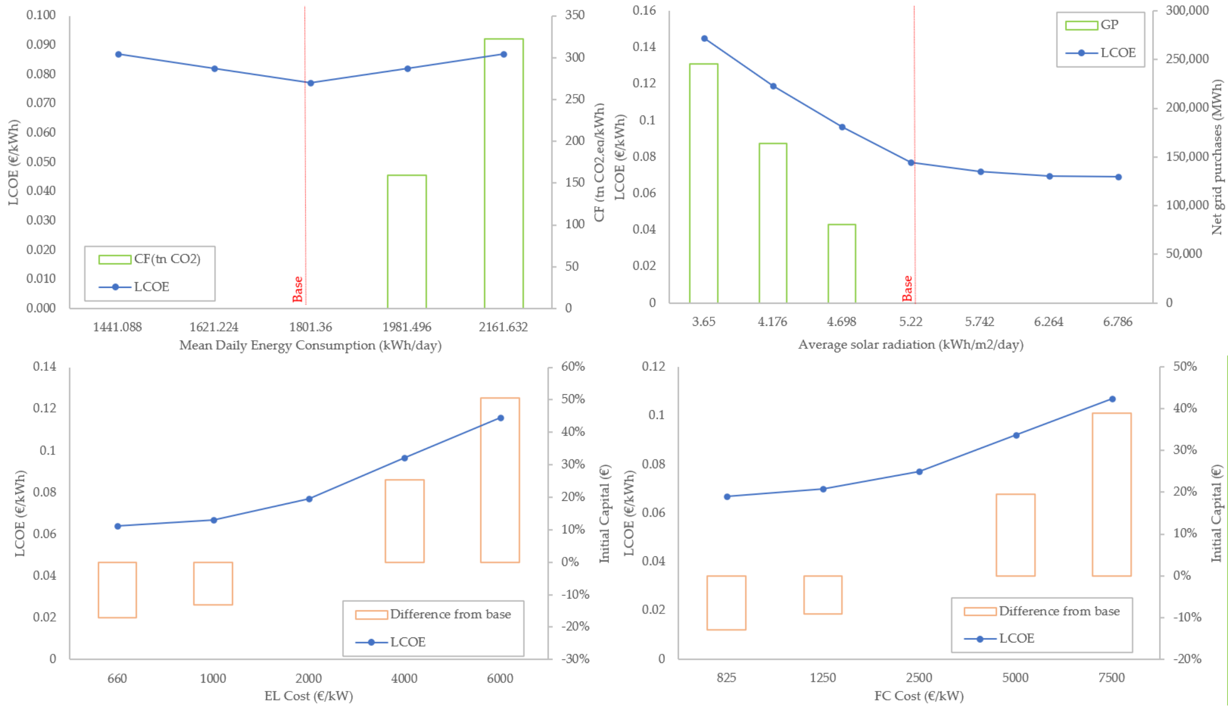

Figure 5.55. Sensitivity analysis for the four varying parameters for the CI cases

Similarly to the non-CI cases, the EL and FC costs were examined as sensitivity variables, as shown in (Figure 5.55). They both significantly influence the system's LCOE due to their high initial capital contributions as the system's most expensive components; the EL has a somewhat bigger influence due to its higher installed power than the FC.

5.4 Evaluation of two micro-grid energy dispatch strategies for a port HRES

5.4.1 Case study detailed description

The main port of Crete's island was selected as a case study with latitude 35.34' N and 25.14 E' longitude (Figure 5.56), which is a large-sized Mediterranean port. Furthermore, Heraklion port was chosen as the most favourable case due to its high HRES and SEMS potential. Since the island's primary income derives from tourism, this port is a top priority for Cretan's well-being. In parallel, the port is among the top 5 largest ports in Greece; its strategic geographical position makes it prone to future structural changes, including implementing the proposed HRES.

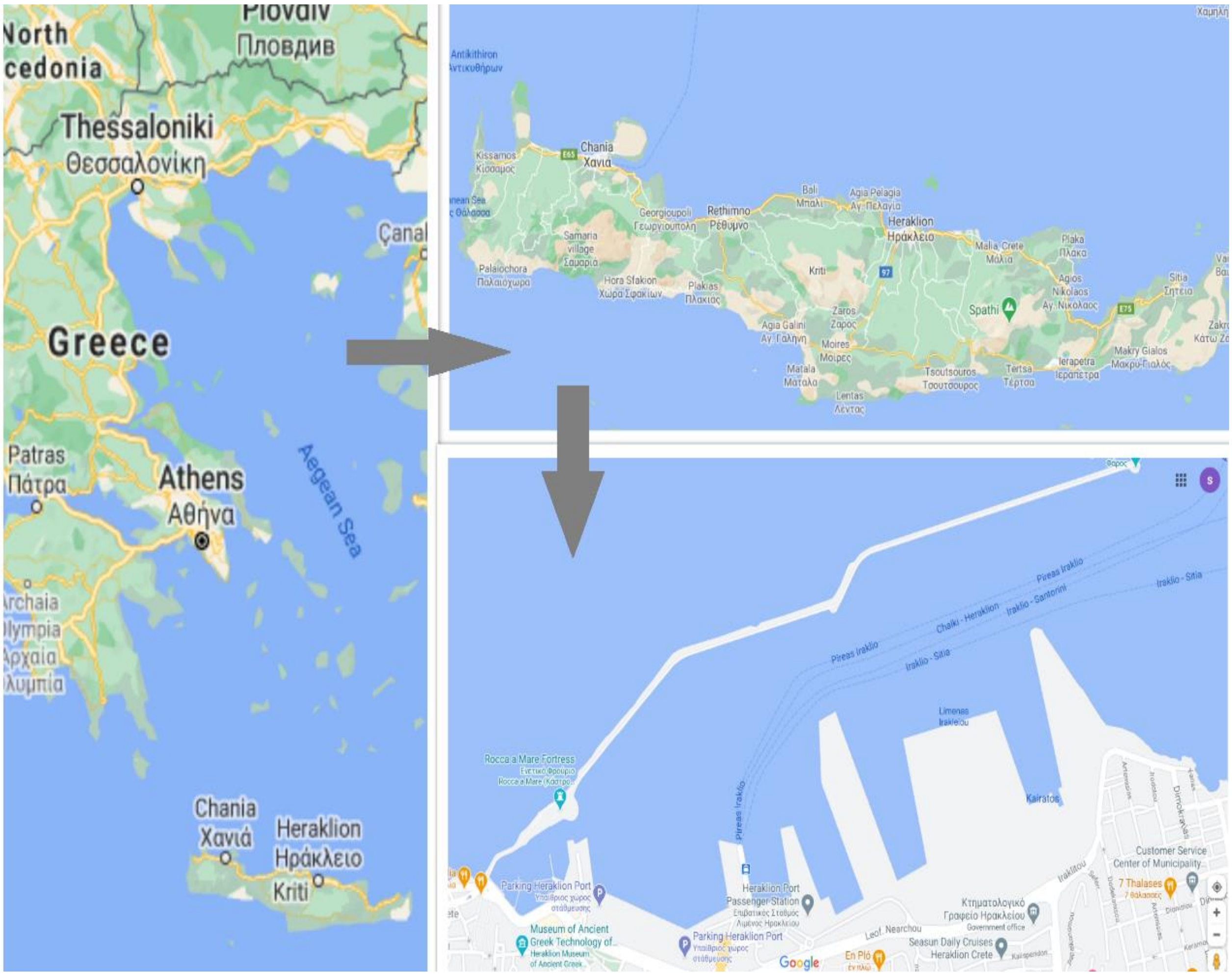

Figure 5.56. The geographical location of the Heraklion port

The acquisition and utilisation of the actual energy demand data are among the advantages of this research compared to most past studies. The proposed HRES should meet any seen and foreseen energy demand, ensuring the high-priority services' unhampered operation and the overall resilience of the port. Seaports' energy demand is stochastic and dynamic, being influenced continuously by uncertain factors and various subsystems.

In this case, the Heraklion port's actual hourly energy load for the past ten years has been acquired, through the smart meters, to overcome and eliminate the stochastic nature of ports' energy demand. The smart meters are installed in three port areas, providing insights regarding the electric demand of the cranes, the outdoor lighting, and the total port's facilities. The diesel machinery is not taken into account for the needs of this research.

Figure 5.57 depicts the histogram and the hourly port's energy demand; the monthly energy loads boxplots. There is a high increase in the energy demand during the summer months due to the increased operations and services related to tourism. The highest energy loads are observed during the night hours due to the strict legislation about port spaces' lighting.

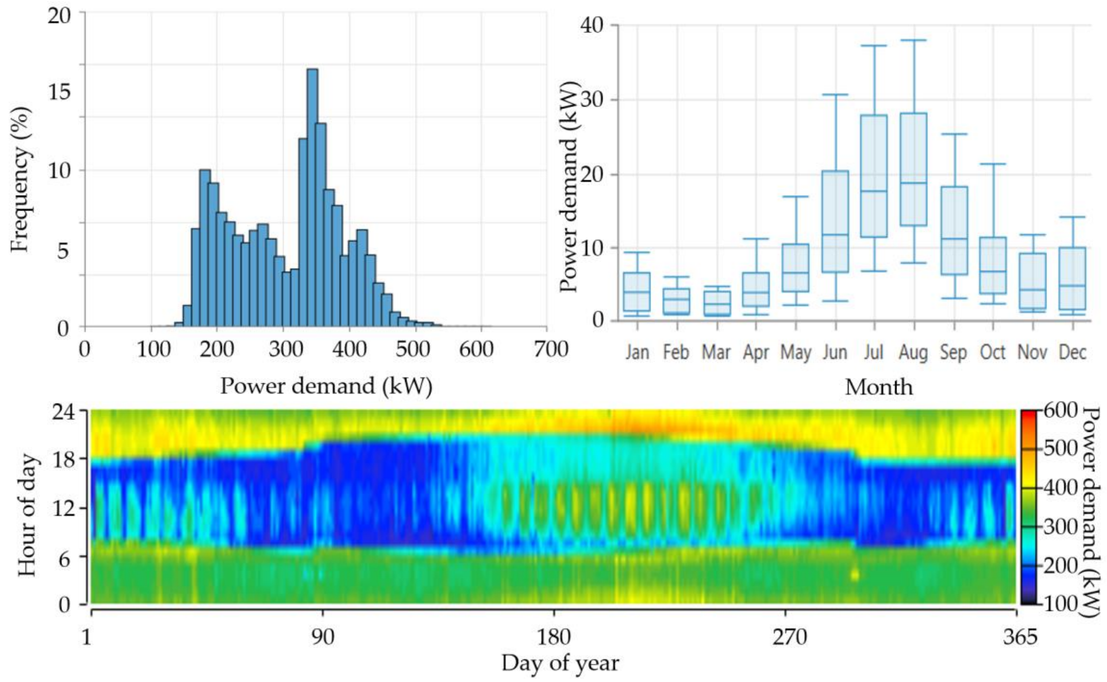

Figure 5.57. Heraklion port's monthly and hourly energy load analysis

Currently, the island's primary electricity grid electrifies the port. Based on the actual hourly energy load data for 2010-2019, the port's average annual demand is 2,676,907kWh, on average 7,329.6 kWh/d. The peak load demand value is noticed during August (533,14 kW). Consequently, the energy demand is high because of its complex and highly energy-demand operations.

The available renewable resources on the port's area are taken from the POWER data access viewer, NASA, and are validated by ground-level measurements taken from the research team; any deviations were less than 10% (Figure 5.58). In addition, f indicates that there are only a few extreme wind speed events on the area (histogram) and the mean monthly wind speed through the year is optimal for WTs; the annual average wind speed is 6.34 m/s.

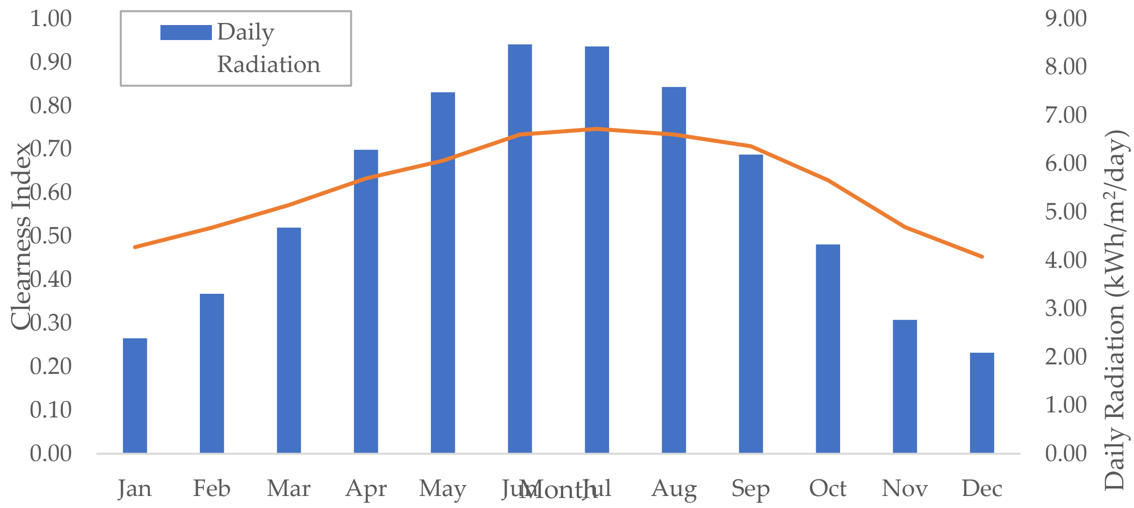

Figure 5.58. Mean monthly solar radiation and clearness index of the study area

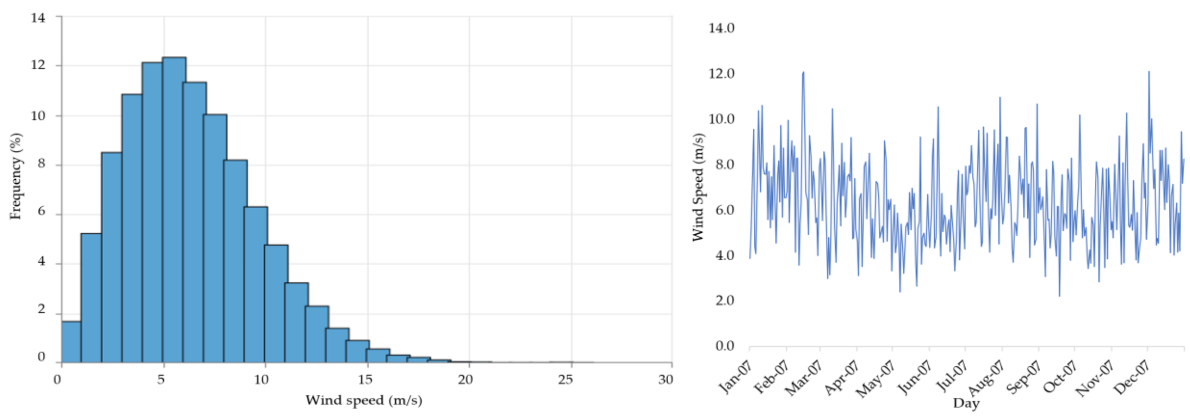

Figure 5.59. Histogram of hourly wind speed and mean monthly wind speed of the study area

5.4.2 Methodology of the hybrid renewable energy system optimum design and smart dispatch for nearly Zero Energy Ports

In this research, an optimisation study regarding an HRES for a Mediterranean port in Crete is carried out according to the port's actual energy profile. The actual power and energy cost tariffs and rates were modeled to ensure the outcomes' reliability. Seventeen scenarios have been examined regarding all the possible combinations of the most mature RES and ESS, picking the optimal one among a pool of ideal solutions according to each case's LCOE, environmental footprint, and future employability. Three different ESS were examined, providing a 24-h autonomy; the power supply's reliability and stability were of utmost importance for the research team. Lastly, a sensitivity analysis was conducted regarding four varying parameters, indicating their impact and significance to the study's outcomes.

5.4.2.1 Selection of the testbed for the proposed study

The main port of Crete's island was selected as a case study with latitude 35.34' N and 25.14 E' longitude, which is a large-sized Mediterranean port typology [361]. Furthermore, Heraklion port was chosen as the most favorable case due to its high HRES and SEMS potential. Since the island's primary income derives from tourism, this port is a top priority for Cretan's well-being. In parallel, the port is among the top 5 largest ports in Greece; its strategic geographical position makes it prone to future structural changes, including implementing the proposed HRES.

5.4.2.2 Data acquisition

The acquisition and utilisation of the actual energy demand data are among the advantages of this research compared to most past studies. The proposed HRES should meet any seen and foreseen energy demand, ensuring the high-priority services' unhampered operation and the overall resilience of the port. Seaports' energy demand is stochastic and dynamic, being influenced continuously by uncertain factors and various subsystems.

5.4.2.3 System's design and adopted methods

Two dispatch strategies have been extensively examined in this research; (a) Cycle Charging (CC) and (b) Peak Shaving (PS). The CC strategy orders the generator to operate at full load or the grid to supply the load demand and, concurrently, charge the ESS. The power sources' optimal combination, at the least cost, is selected in each timestep by calculating their fixed and marginal costs. No excess electricity is generated or supplied; the smart microgrid controller ramps up the generator's output or the grid in that optimal combination of its rated capacity [384].

The PS strategy is based on a '48-h projection' in every timestep and on the month's optimised power demand limits. The microgrid controller knows the future power demand, grid's rate schedule, and RES production. It optimises and recognises the least cost system by reducing the possible demand charges; if possible, the controller participates in energy arbitrage. PS attempts to discover the lower-cost grid power demand per month by adjusting and testing the given system configuration. Consequently, the least monthly peak demand that can supply the required load alongside the RES and ESS is picked. The system's economics are calculated only if the system is properly operating and the load demand is being served in each timestep without overcoming the peak demand limit.

5.4.2.4 Mathematical modelling and system components characteristics

After setting the smart algorithm, the suggested components and the preferred smart dispatch strategy are defined. After simulating all the possible combinations of the desired components, the optimal economic solution is indicated, based on the total system's Net Present Cost (NPC) (Figure 5.60).

The RES power energy output is calculated by using Equation 60 [363]. Y_{PV} is the rated capacity of the PV array in kW, f_{PV} is the PV derating factor (%), G_T is the solar radiation in the current time step (kW/m^2), $G_{T,STC}$ is the incident radiation at standard test conditions, α_Q is the temperature coefficient of power (%/°C), T_C is the PV cell temperature in the current time step (°C), and $T_{C,STC}$ is the PV cell temperature under standard test conditions (25 °C). The derating factor is being used due to the PV arrays' possible power losses due to soiling, wiring, and aging.

$$P_{PV} = Y_{PV} \times f_{PV} \times \left(\frac{G_T}{G_{T,STC}}\right)[1 + a_\rho\left(T_c - T_{C,STC}\right) \quad (60)$$

The WT power output is calculated using Equation 61. P_r is the wind turbine rated power, V_r is the rated wind speed in m/s, $V_{cut\text{-}in}$ is the WT's cut-in speed, and $V_{cut\text{-}out}$ is the WT's cut-out speed.

$$P_{WT} = \begin{cases} 0 & V < V_{cut-in} \; and \; V \geq V_{cut-out} \\ \dfrac{P_r \times (V - V_{cut-in})}{(V_r - V_{cut-in})} & V_{cut-in} \leq V \leq V_r \\ P_r & V_r \leq V < V_{cut-out} \end{cases} \quad (61)$$

V is the actual wind speed that changes according to the WT's hub height and is estimated using Equation 62. V_{base} is the wind speed at the base height H_{base}. The exponent α is proportionate to the climate conditions (temperature, season, time of the day, roughness); α is usually equal to 0.143 under steady wind speed. The density ratio equals the actual air density (ρ) divided by the air density at standard temperature and pressure (ρ_0 =1.225 kg/m^3). The power is multiplied by the density ratio as shown in Equation 63.

$$V = V_{base\times}\left(\frac{H}{H_{base}}\right)^\alpha \quad (62)$$

$$P_{WT} = \left(\frac{\rho}{\rho_0}\right) \times P_{WT,STP} \quad (63)$$

Three different types of ESS are examined. They are used to store the surplus RES energy and serve the PS technique. The ESS energy can be estimated using Equation 64; $Q_{ESS,0}$ is the initial ESS charge, V_{ESS} is the battery's voltage, and I_{ESS} is the ESS current.

$$Q_{ESS} = Q_{ESS,0} + \int_0^t V_{ESS} \times I_{ESS} dt \quad (64)$$

The required ESS's state-of-charge is given by Equation 65, where $Q_{ESS,\ max}$ is the maximum allowable ESS's charge power; it is estimated using the kinetic battery model (Equations 66, 67, 68, and 69); $\eta_{ESS,c}$ is the efficiency of the charge storage. More detailed information can be found in the research work of Baneshi and Hadianfard [364]. k is the storage rate constant (h^{-1}), Q_1 is the ESS's available energy in the initial time step (kWh), Δt is the timestep's duration (h), Q is the initially available energy (kWh), c is the ESS's capacity ratio, a_c is the ESS's maximum charge rate (A/Ah), $Q_{ESS,max}$ is the total ESS's capacity (kWh), N_{ESS} is the number of ESS, I_{max} is the ESS's maximum charge current (A), and V_{nom} is the ESS's nominal voltage.

$$B_{SOC} = \frac{Q_{ESS}}{Q_{ESS,max}} x100 \ (65)$$

$$Q_{ESS,max} = \frac{\min\left(P_{ESS,max,kbm} \times P_{ESS,max,mcr} \times P_{ESS,max,mcc}\right)}{\eta_{ESS,c}} \ (66)$$

$$P_{ESS,max,kbm} = \frac{k \times Q_1 \times e^{-k\times\Delta t} + Q \times kc(1 - e^{-k\times\Delta t})}{1 - e^{k\times\Delta t} + c(k \times \Delta t - 1 + e^{-k\times\Delta t})} \ (67)$$

$$P_{ESS,max,mcr} = \frac{1 - e^{-\alpha_c \Delta t} \ \ (Q_{ESS,max} - Q_{ESS})}{\Delta t} \ (68)$$

$$P_{ESS,max,mcc} = \frac{N_{ESS} \times I_{max} \times V_{nom}}{1000} \ (69)$$

Lastly, the bi-directional inverter's power output is given by Equation 70. P_{out} is the output power on the AC grid; P_{in} is the input power to the inverter on the DC grid, η_{inv} is the inverter's efficiency. In this study, the inverter's efficiency is taken as 0.95.

$$P_{out} = P_{in} \times \eta_{inv} \ (70)$$

The economic modelling and the used equations are used as follows:

The total system's cost is the sum of the PV cost (C_{pv}), the WT cost (C_{WP}), the grid cost (C_{grid}), the ESS cost (C_{ESS}), and the converter cost (C_{conv}):

$$C_{system} = C_{PV} + C_{WT} + C_{grid} + C_{ESS} + C_{conv} \ \ (71)$$

Costs include capital costs, replacement costs, O&M costs, fuel costs, and the grid's energy billing. Profits include salvage value and grid sales. The system's NPC is calculated by using equation 72:

$$C_{NPC} = \frac{C_{tot,ann}}{CRF(i,\eta)} \ (72)$$

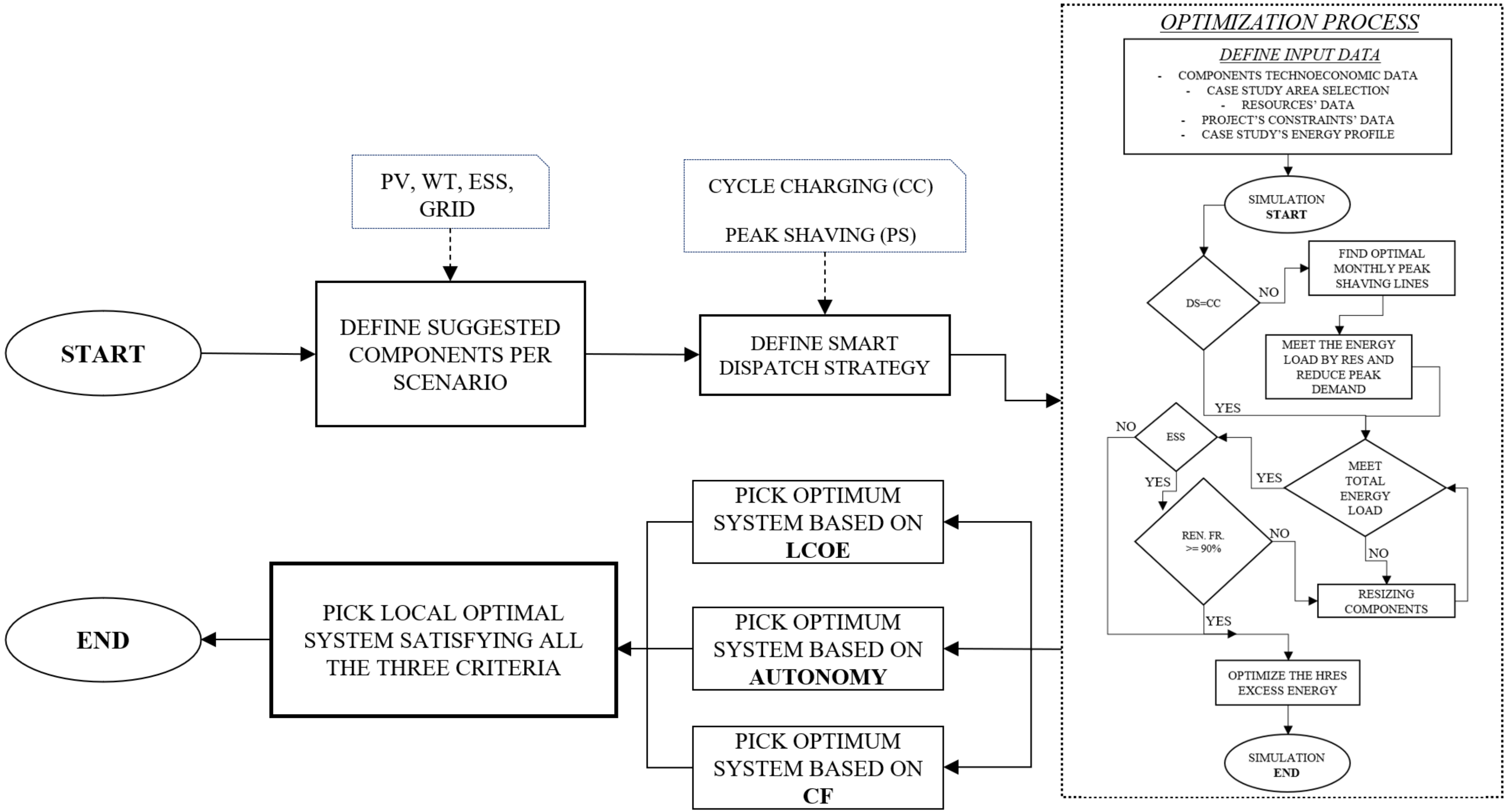

Figure 5.60. Proposed smart algorithm's flowchart

Besides, the total NPC is the value by which the LCOE is calculated divided by the whole electric load served (E_{served}) [363]:

$$LCOE = \frac{NPC}{E_{served}} \quad (73)$$

Where $C_{tot,ann}$ is the total annual cost (€/year), and CRF is the capital recovery factor as given by equation 74, where i is the discount rate (%), n=the number of years, and η is the project lifetime (y). The discount rate is given by equation 75.

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (74)$$

$$i = \frac{i' - f}{1 + f} \quad (75)$$

The discount rate is 8.0%, and the inflation rate is 2.0%[363].

The payback period (PP) is used to evaluate the HRES feasibility; it is estimated by using Equation 76. C_0 is the initial capital cost, and C_{if} is the income cash's annual flow.

$$PP = \frac{C_0}{C_{if}} \quad (76)$$

To estimate the Internal Rate of Return (IRR), we assume that $NPC = 0$. Then the IRR is calculated by using equation 77:

$$NPC = 0 = \sum_{t=1}^{T} \frac{C_t}{(1 + IRR)^t} - C_0 \quad (77)$$

As the Greek market's resellers indicated, the economy of scale is considered for the PV and WT costs. The Carbon Footprint (CF) is estimated by using equation 78. $E_{grid,net}$ is the net energy purchased from the grid, RF is the island's renewable fraction (%), and PI is the pollutants index for the grid's function (0.989kg$CO_{2,eq}$/kWh).

$$CF = \sum_{t=1}^{T} E_{grid,net} \times RF \times PI \quad (78)$$

The components' techno-economic characteristics are presented in Table 5.16. More details about the two RES are available in the Appendix.

Table 5.16. Techno-economic characteristics of the suggested components

Photovoltaic array – LONGi Solar LR4-60HPH			
Capital cost (€)	Capacity (kW)	Capital (€)	Cost (€/kWp)
	1	1400	1400
	10	9000	900
	50	40,000	800
	100	75,000	750
	500	350,000	700
	1000	600,000	600
O&M Cost (€/yr)	Capacity (kW)	Capital (€/yr)	
	1	10	
	10	100	
	50	500	
	100	1000	
	500	5000	
	1000	10,000	
Efficiency (%)	20.6		
Lifetime (yr)	25		
Derating factor	88%		
Wind Turbine – Eunice EW16 Thetis 50kWp			
Capital cost[2] (€)	Scaled		
	Quantity	Capital (€)	Cost (€/kWp)
	1	210,000	4200
	5	750,000	3000
	10	1,250,000	2500
	20	2,000,000	2000
Lifetime	25		
Hub Height	22.03		

Lead Acid Battery (LA)	
Capacity (kWh)	8.03
Nom. Voltage (V)	2
Max capacity (Ah)	4014
Lifetime@50%DoD(yr)	20
Capital cost (€/kWh)	165
Li-Ion Battery (LI)	
Capacity (kWh)	7.68
Nom. Voltage (V)	51.2
Nom. capacity (Ah)	150
Lifetime@75%DoD(yr)	25
Capital cost (€/kWh)	533
Vanadium Redox Flow Battery (VRFB)	
Capacity (kWh)	1238
Nom. Voltage (V)	700
Nom. capacity (Ah)	1769
Lifetime@90%DoD(yr)	25
Capital cost (€/kWh)	200
AC/DC Bi-directional Converter[1]	
Inverter efficiency (%)	95
Rectifier efficiency (%)	95
Lifetime (yr)	15
Smart Microgrid Controllers	
Cycle Charging (CC)	
Peak-Shaving (PS)	

[1]Inverter's capital cost is included in the PV's capital cost

The last part of this methodology is about the port's energy billing. The electricity bill is studied under two billing tariffs:

(a) the energy consumption during the peak hours (07:00-23:00) and

(b) the energy consumption during the off-peak hours (00:00-07:00).

The energy tariffs are 11.96 c€/kWh and 9.94 c€/kWh, respectively. However, there are power demand charges for the monthly peak power demand during specific hours of the day, incorporating the time-of-use (TOU) tariff type. The corresponding demand charges are 8.96 €/kWp for the high peak hours (11:00-14:00) and 6.66 c€/kWh for the rest hours (07:00-23:00), excluding the late-night ones (00:00-07:00).

Seventeen different scenarios regarding the suggested HRES were examined, evaluated, possible combinations of the suggested components, and dispatch strategies. The research team has picked the two most optimal cases based on specific criteria. The selection criteria were about the least net present cost, the least LCOE, the least payback period of the investment, and lastly, the environmental footprint of each scenario. Two SEMS (microgrid controllers) were utilised to increase the system's overall efficiency. The suggested PV/WT/ESS HRES is grid-connected, but the case of an autonomous port system has also been evaluated (Table 5.17).

Several assumptions have been made for this study's needs, as follow:

- The components' sizing did not consider the manufacturers' restrictions;
- ESS lifetime was subject to the estimated annual life-cycles, and their responsible inverter was included in their initial cost;
- No O&M costs were considered for the components, except for the DG
- The bi-directional inverter's cost was integrated on the PV arrays cost
- The proposed RES can be installed in any place connected to the electricity grid due to the lack of space inside the port's area.

Table 5.17. Different HRES combinations for the examined scenarios

Case	Grid	NM	DG	PV	WT	ESS	DS
1	✓	x	x	x	x	x	x
2	✓	x	x	x	x	OA	CC
3	✓	x	x	x	x	24A	PS
4	✓	x	x	x	x	OA	PS
5	✓	x	x	✓	x	OA	CC
6	✓	x	x	✓	x	24A	PS
7	✓	x	x	✓	x	OA	PS
8	✓	x	x	✓	✓	OA	CC
9	✓	x	x	✓	✓	24A	PS
10	✓	x	x	✓	✓	OA	PS
11	✓	✓	x	x	x	X	CC
12	✓	✓	x	✓	x	OA	CC
13	✓	✓	x	✓	x	24A	PS
14	✓	✓	x	✓	x	OA	PS
15	✓	✓	x	✓	✓	OA	CC
16	✓	✓	x	✓	✓	24A	PS
17	✓	✓	x	✓	✓	OA	PS

OA stands for optimal autonomy based on economic criteria

24A stands for the 24-h autonomy of the port's operations

5.4.3 Outcomes of the hybrid renewable energy system optimum design and smart dispatch for nearly Zero Energy Ports

A detailed techno-economic analysis of the proposed HRES, incorporating two SEMS dispatch strategies, is presented based on the actual 10-year average port's energy demand data, the port's energy pricing scheme, and the components' current market costs. In addition, a sensitivity analysis is also carried out on four varying parameters. This study aims to provide an insight into the impact of the two dispatch strategies on the HRES's efficiency, the importance of integrating SEMS in HRES, and a holistic view of all the possible viable solutions that ports can employ the way towards sustainability. The CC dispatch strategy is widely known in HRES studies. Nine scenarios have been considered using CC; five of them were about a grid-connected HRES without the Net Metering (NM) capability, and the rest four of them were about the same grid-connected HRES capable of using the NM. A 20% demand charges increase was inserted to represent the NM's utility cost. The proposed system's baseline scenario contains just the electricity grid and has an LCOE of 14.9 c€/kWh; the monthly operating expenses are depicted in Figure 5.61. The power demand costs are relatively high, accounting for 25% of the total annual expenditure.

The port's actual energy demand does not present high or frequent hourly extreme peaks; the monthly peak demand value is near the mean monthly required energy. At first glance, someone would expect that peak shaving would have a low impact on energy efficiency and future energy and cost savings. Surprisingly, Figure 6 indicates that the peak demand charges are high enough due to the high energy loads. The mean daily energy demand indicates that 7,3 MWh, equivalent to 430 Greek households' mean daily energy demand. The port can be considered a small town or an energy community in terms of energy consumption and operations and services complexity. The main difference is that ports tend to peak their power demand during night hours because of their energy-demanding lighting infrastructures and the ships-on-berth.

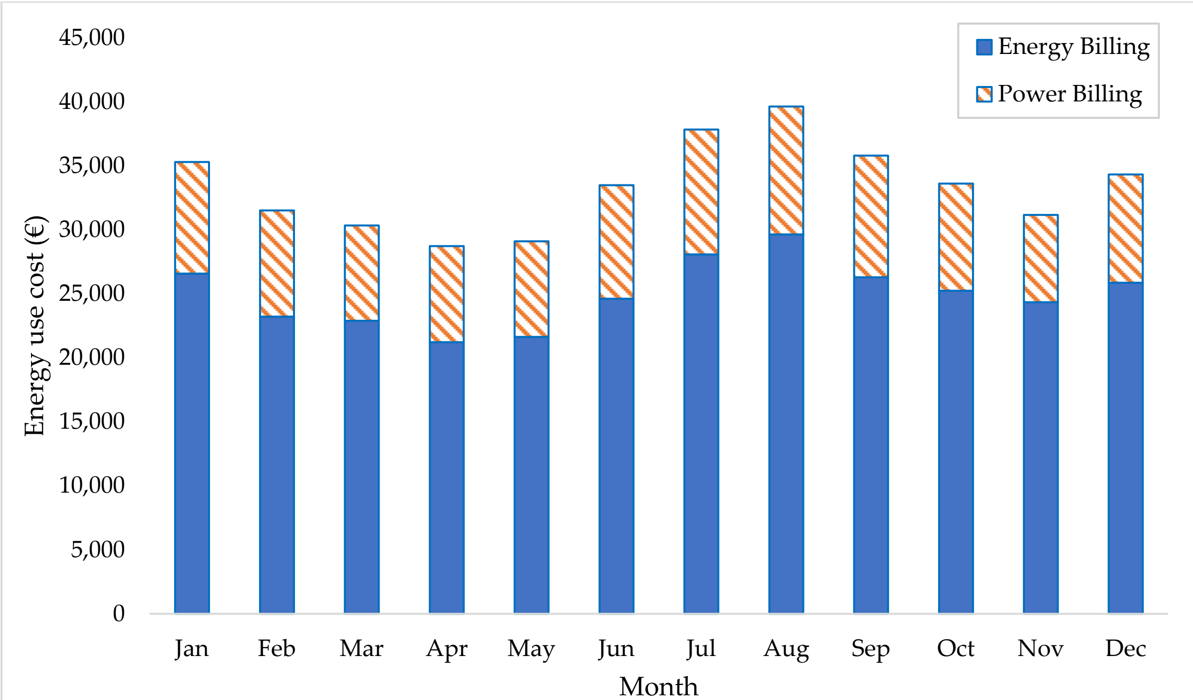

Figure 5.61. Port's monthly energy use and power demand costs

The energy use cost is disproportionally connected to its energy consumption due to unforeseen high-power demand events that often occur at ports (**Figure 5.61**). As expected, the highest peak demand is observed during the summertime being linked to tourism; concerning the highest energy consumption, it is observed during both summer and winter months due to the increased lighting needs during wintertime and tourism's impact during summertime.

The proposed HRES were based on two types of main power supply: (a) the electricity grid without NM, and (b) the electricity grid taking advantage of the NM utility.

5.4.3.1 Grid-connected HRES without NM

A total number of ten scenarios were simulated regarding being grid-connected without activating the NM functionality. The most optimal HRES (LCOE and CF) per scenario was moved in the candidate pool; two scenarios were picked as the most optimal from the optimal solutions' pool (**Figure 5.62**).

The selected-optimal HRES were chosen according to three specific criteria; the first criterion is the proposed HRES LCOE. The second criterion is the port's operations reliability and stability insurance, while the third criterion was the CF.

Ports are responsible for ensuring the unhampered supply of their services unaffected by possible grid outages. Consequently, the research team calculated the optimal number of ESS components to provide the HRES with 24-h autonomy. Besides, two SEMS (dispatch strategies) are examined and compared. For the PS strategy, two cases were examined per HRES; an HRES incorporating 24-h autonomy and a second one without autonomy restrictions could serve the PS strategy.

The lowest-NPC scenario is chosen as optimal only if the suggested HRES's CF is zero. The proposed HRES supplies all the required energy to cover the energy needs. As a result, the two optimal scenarios were the PV/WT/ESS ones controlled by the PS strategy. The optimal HRES's techno-economic and environmental outcomes are presented in Table 5.18.

The PS strategy's efficiency compared to the CC and the baseline case can be observed in Figure 5.63. The demand limits indicate that the power deriving from the grid cannot exceed this value, and the smart dispatch controller has already projected and taken care of this event. The high peak power demands are smartly eliminated, effectively reducing the power charges. The LCOE of the proposed HRES of scenario 9 (12.9c€/kWh) is higher than scenario 10 HRES's (8.2c€/kWh) because of the initial ESS investment cost overdimensioning to provide 24-h autonomy of the services, on peak demand.

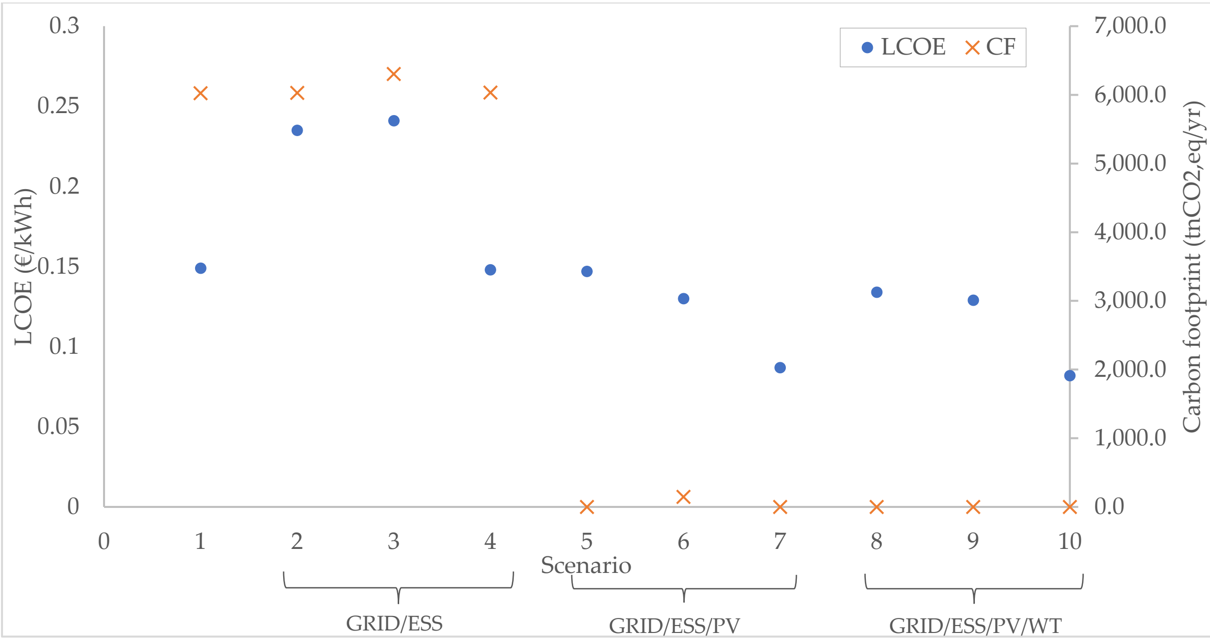

Figure 5.62. LCOE and CF of the optimal solutions per scenario (1-10) of the grid-connected case without NM

The WT HRES minimise further the LCOE, leading to the most feasible solution among the optimal options. However, higher initial investment is required (Figure 5.62). Regarding the first two without RES scenarios, the LCOE is higher than the baseline due to the initial capital investment in ESS and the absence of green energy generation. Meanwhile, the LCOE is slightly lower in scenario 4 due to the power limits that have been set, incorporating the PS strategy.

LCOE is dramatically modified by implementing RES (scenarios 5-10). Scenarios 6 and 9 proved that the 24-h autonomy of the power supply is more effective when the PS strategy is used for the microgrid's control. Meanwhile, scenarios 7 and 10 indicated that the LCOE is increased the higher the autonomy is. For instance, in scenario 7 a 21-h autonomous HRES is suggested while a 24-h autonomous HRES is proposed in scenario 6; their LCOE are 8.7c€/kWh and 13.0c€/kWh, respectively, due to the additional investment for ESS.

The CF is inversely connected to the renewable penetration in the main grid. The grid energy purchases are meant to be almost equal to zero into an nZEP, resulting in sustainable infrastructure. Scenario 3 suggests a system with higher CF than the baseline as more energy is required to be purchased from the grid to fulfil the needs of the 24-h autonomy. Meanwhile, on scenarios 5,7,8,9 and 10 the CF is zero due to the excess RES energy production, which overlies the grid purchases.

As seen, HRES of scenario 6 has a positive CF, meaning that energy deriving from the electricity grid is needed to achieve 24-h autonomy.

Table 5.18. Techno-economic and environmental characteristics of the two optimal scenarios for the grid-connected HRES without NM

Scenario	PV (kW)	WT (kW)	ESS (pcs)	LCOE (c€/kWh)	GP[1] (kWh)	Autonomy (h)	Ren.Fr. (%)
9	1,756	100	12	12.9	-74,131	24	91.3
10	626	650	3	8.2	-298,290	10	90.0

[1]GP refers to the net grid purchases (GP=Grid purchases - Grid sales)

Scenario's 10 suggested HRES can ensure the regular port operation for at least 10-h. Consequently, the cost of providing the power supply for an extra 14 h is high. Although the LCOE of the 24-h autonomous HRES is higher than this of the 10-h autonomy, both the systems are feasible; the baseline LCOE equals 14.9 c€/kWh. There is a 13.4% and a 45% decrease, respectively. The IRR of the first case is equal to 6.2%, and the second one is 11.9%. The latter was the highest IRR among all the feasible solutions, further demonstrating the chosen-optimal HRES's concreteness and applicability.

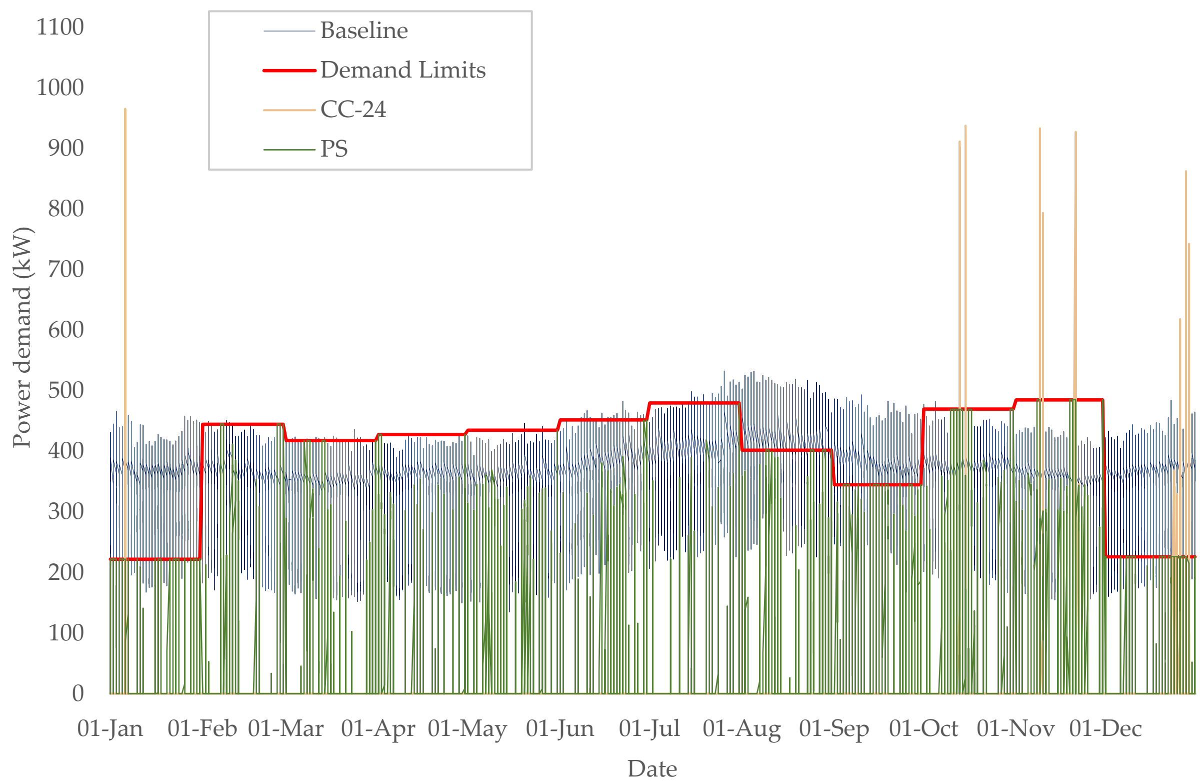

Figure 5.63. Hourly power demand among the two dispatch strategies and the baseline scenario

The examined smart control strategies for the most optimal-picked scenarios (7, 10) do achieve their primary goal by diminishing the grid purchases, proposing the economically and environmentally optimal solution (Figure 5.63). As for the CC strategy, the grid purchases are diminished while there are still some peaks throughout the year due to the stochastic nature of most RES in energy production. These peaks are higher than the baseline's, proving that even if the energy costs are decreased, the demand billing is not that much decreased.

However, as for the PS-controlled optimal scenario, the monthly demand limits restrict the energy demand to the optimal peaks, leading to lower peaks. Indicatively, especially in summer and winter months where the peak demand was observed during the past years, the limits restrict energy consumption, leading to noteworthy billing reductions. Thus, the suggested HRES's LCOE is reduced, resulting in a fruitful and feasible solution.

VRFB is chosen as the ESS for the optimal scenarios due to the lower initial cost than the other alternatives; the suggested HRES has a lower NPC than the other two systems. Indicatively the LCOE was 13.9 c€/kWh for the LA ESS, and 22.2 c€/kWh for the LI (scenario 9). As for scenario 10, the LCOE was 8.5 c€/kWh for the LA ESS and 7.92 c€/kWh for the LI. LI HRES presented lower LCOE, but the suggested solution's NPC was higher than the optimal-picked case; the IRR was lower (8.5%).

5.4.3.2 Grid-connected HRES with NM

For the case of the grid-connected HRES incorporating the NM capability, seven scenarios were simulated. The cost of using the NM functionality is integrated as a 20% increase in the power demand charges. Accordingly, the baseline LCOE equals 15.7 c€/kWh. The initial CF is 6,023tn$CO_{2,eq}$/year, making it a top priority for port authorities to reduce. Similar to the grid-connected HRES without NM, two optimal scenarios are picked among the candidates. The LCOE and CF per candidate scenario are presented in Figure 5.64.

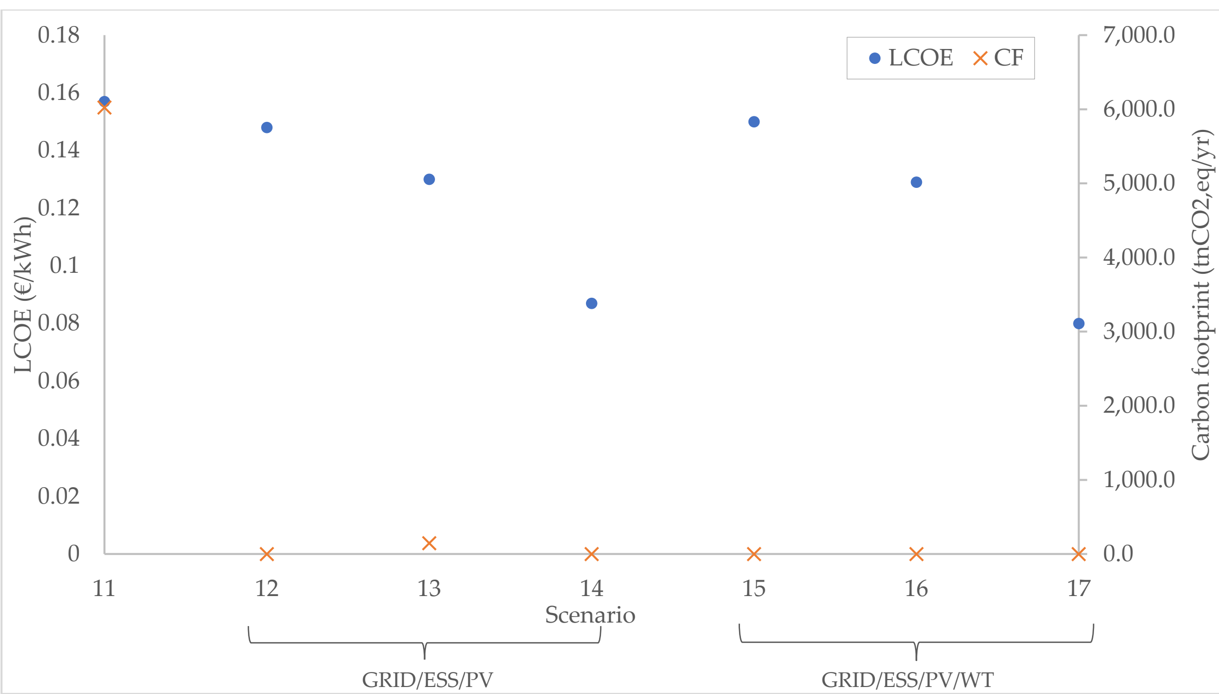

Figure 5.64. LCOE and CF of the optimal solutions per scenario (11-17) of the grid-connected case with NM

In the examined scenarios' LCOE is lower than the baseline ones (Figure 9). The PS strategy is more energy-efficient than the CC; the monthly demand limits result in substantial cost savings. The PS strategy's effectiveness in the NM grid-connected HRES power demand can be observed in Figure 5.65. Although the overall energy bill savings are less for the PS case than the CC one, the initial required capital is less for the PS case. The CC strategy requires higher RES penetration to fulfil its goals, while the PS can serve the limited power demand incorporating fewer resources.

Similarly, for the case on the NM grid (Figure 5.64), the scenarios' suggested HRES proved that the LCOE is lower when WTs are incorporated due to the night-hour energy production. Scenario 17 proved the best scenario, economically and environmentally; the suggested HRES provides a 10-h autonomy while the LCOE is equal to 8c€/kWh and the CF is zero. Nevertheless, scenario 16 is optimal for this research work, ensuring 24-h power supply autonomy through the proposed ESS, proposing an LCOE of 13c€/kWh.

Consequently, even for the NM case, a more considerable initial investment must provide the much-coveted 24-h power supply autonomy and ensure the operations and services. Therefore, the operating costs and the LCOE are proportionally connected to the required initial capital for the surplus ESS. Meanwhile, scenario 13 is the only one that proposed an inadequate HRES in fully meeting the energy demand, leading to grid energy purchases.

The energy-bill savings are substantial as the PS-based systems are undersized compared to the CC ones, and thus the overall power demand is lower for the RES to cover. Therefore, the initial capital cost is lower, achieving even better GHGs diminishing and climate change mitigation results. Besides, the power demand charges are lower, leading even higher to cost savings. On the contrary, the lower LCOE may lead to substantial operating cost savings, lower PP, and higher IRR. Consequently, the two preferred optimal scenarios are the PS-controlled PV/WT/VRFB HRES. The technical characteristics, alongside the environmental and economic outcomes are presented in Table 5.19.

The VRFB HRES are the selected optimal cases again; the VRFB HRES are more economically feasible and lead to the lowest operating costs than the other ESS types. For the HRES of scenario 17, the LCOE of the LA HRES is 6.3 c€/kWh, while the LI HRES LCOE is 5.4 c€/kWh. Unfortunately, due to the high initial capital costs and the increased operating costs, the IRR of these HRES is lower than the selected ones. As for scenario 16, the LA HRES presents an LCOE of 14.0 c€/kWh, while the LI HRES's LCOE is 23.4 c€/kWh. Therefore, the VRFB ESS seems to be the ideal solution for the grid-connected HRES, either with NM enabled either not.

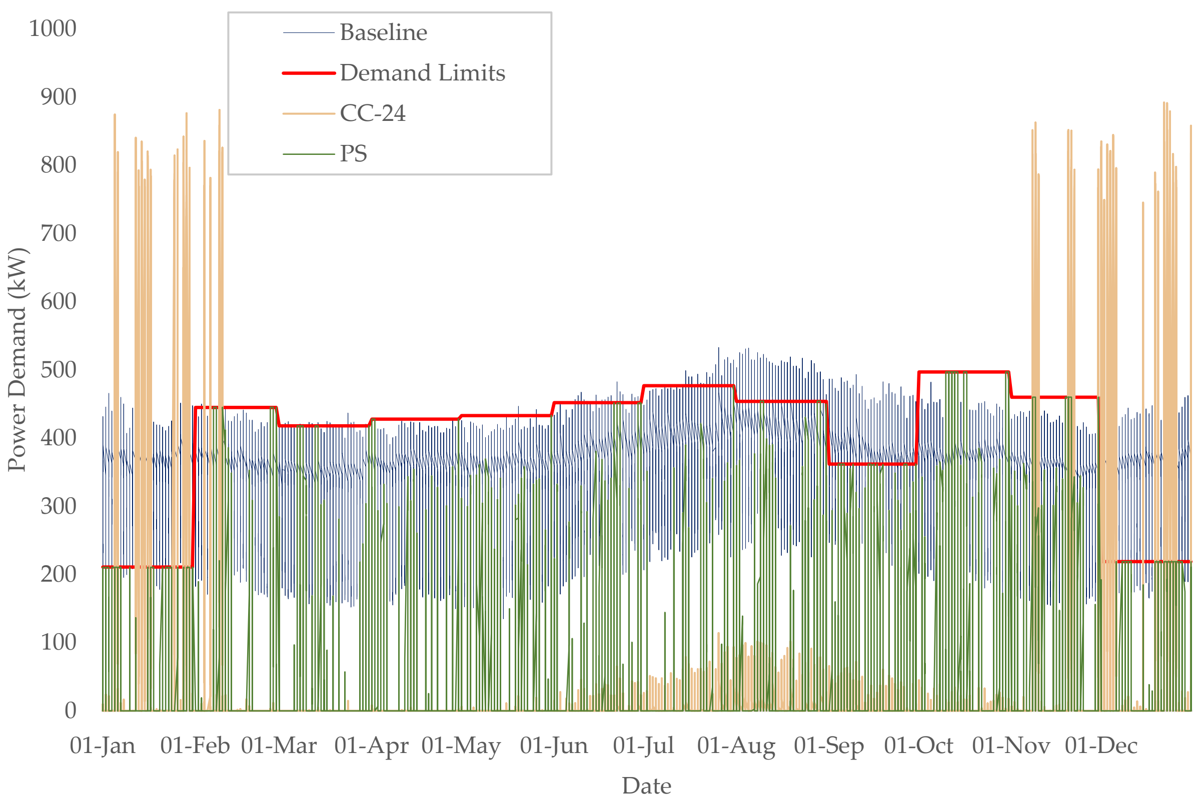

Figure 5.65. Hourly power demand of the two dispatch strategies and the baseline scenario (NM)

Table 5.19. Techno-economic and environmental characteristics of the two optimal scenarios for the grid-connected HRES with NM

Scenario	PV (kW)	WT (kW)	ESS (pcs)	LCOE (c€/kWh)	GP[1] (kWh)	Autonomy (h)	Ren.Fr. (%)
16	1,756	100	12	12.9	-74,131	24	91.3
17	535	700	3	8.0	-339,256	10	90.1

[1]GP refers to the net grid purchases (GP=Grid purchases - Grid sales)

The least-LCOE scenario's PV array's installed power is three times lower than the 24-h autonomous case. In this case, the PS strategy picks more WTs due to power generation's capability during night-time when the PVs are shut off. The ESS cannot provide all the required energy to the system, and the peak power demand limits may be exceeded. Due to the high initial ESS costs, it is advisable to employ additional WTs to serve the night load than invest in ESS for the time being.

As in the non-NM case, there are some higher peak energy demands than the baseline case, for the CC strategy (Scenario 15). However, even if the energy consumption is lowered and thus the energy billing, the higher peak demands lead to high demand costs. Similarly, the PS technique (Scenario 17) achieves the most optimal results by setting monthly demand limits. The outcomes of this strategy could be even better if the energy supply company included billing for the late-night hours of the day regarding the power demand. It is noteworthy that the NM case peaks (Scenario 15) are more than this of the non-NM case (Scenario 8), enhancing the effectiveness of the PS technique. For both the cases (NM or not) the selected optimal HRES have substantial renewable penetration on the port's microgrid, leading to zero GHG emissions for the operations. The nearly Zero Energy Port (nZEP) concept is viable, feasible, and can be successfully implemented in other similar ports.

The least autonomous HRES (scenario 10) provides the grid with more electricity due to the suggested ESS capacity shortage; there is no enough energy storage to store the excess RES generated energy. After enabling the NM functionality, this issue is fixed as the excess energy is supplied to the electricity grid, offsetting the grid purchases; the net GP is considered for the energy billing. The techno-economic and environmental information of each scenario's optimal solution is presented in Table 5.20.

Table 5.20. Optimal economic and environmental outcomes of the 17 simulated scenarios

	Scenario Number	NPC (M€)	LCOE (c€/kWh)	PP (yr)	IRR (%)	NGP (kWh)	CF ($tnCO_{2,eq}/yr$)	ESS	Autonomy (h)
Grid-connected	1	5.16	14.9	-	-	2,675,318	6,023.4	-	-
	2	8.13	23.5	-	-	2,677,776	6,028.9	VRFB	24
	3	8.32	24.1	-	-	2,799,745	6,303.5	VRFB	24
	4	5.15	14.8	8.2	11.4	2,679,262	6,032.2	Li-Ion	0.2
	5	5.67	14.7	14.6	4.7	-162,873	0.0	VRFB	24
	6	4.95	13.0	12.27	6.4	64,924	146.2	VRFB	24
	7	3.80	8.7	9.2	9.9	-298,290	0.0	VRFB	21
	8	5.71	13.4	14.5	4.8	-582,769	0.0	VRFB	24
	9	5.03	12.9	12.5	6.2	-74,131	0	VRFB	24
	10	3.48	8.2	7.8	11.9	-298,290	0.0	VRFB	10
Grid-connected (NM)	11	5.43	15.7	-	-	2,675,318	6,023.4	-	-
	12	5.7	14.8	13.7	5.2	-138,630	0.0	VRFB	24
	13	4.9	13.0	11.6	7.1	64,927	146.2	VRFB	24
	14	3.5	8.7	8.5	10.8	-529,685	0.0	VRFB	21
	15	5.7	15.0	13.8	5.2	-116,631	0.0	VRFB	24
	16	5.03	12.9	11.8	6.8	-74,131	0.0	VRFB	24
	17	3.44	8.0	6.8	14.1	-339,256	0.0	VRFB	10

5.4.3.3 Sensitivity Analysis

An LCOE sensitivity analysis was conducted for the two dispatch strategies to examine and analyse the impact of uncertainties on the suggested HRES. Although the sensitivity analysis is performed for all the optimal scenarios, for brevity's sake, only for the optimal-selected NM 24-h autonomous scenario for each dispatch strategy is shown. Solar radiation, wind speed, hours of autonomy, and mean daily energy consumption are the varying parameters for the LCOE of the HRES. The research team examined the effect of the different discount and inflation rates for the optimal HRES. It has been proved, as expected, that there is a high impact on the overall HRES economic outcomes, and a possible alteration would affect the study's conclusions. The impact's level is analogous to the indexes' alteration.

5.4.3.3.1 Sensitivity analysis for the CC strategy

Figure 5.66 presents the outcomes of the sensitivity analysis for the four varying parameters under the CC strategy. Speaking about the mean daily energy consumption, the LCOE is reducing until it meets the current state. After this, the LCOE increases alongside energy consumption as grid energy is needed; the CF is rising. The HRES is optimal for the port's case under the CC strategy. As for the grid's autonomy and reliability, the cost savings increase for the bigger than 12-h autonomous HRES; the previous values follow a decreasing trend. The LCOE increases concurrently with the HRES's autonomy. This can be attributed to the willingness to pay for the extra energy supply's safety. Lastly, as expected, the PVs LCOE decreases as the solar resource is increasing regarding renewable resources. Contrary, the WT's energy contribution is so low that the wind resources hardly impact the HRES's LCOE.

5.4.3.3.2 Sensitivity analysis for the PS strategy

Figure 5.67 presents the findings of the sensitivity analysis for the four varying parameters under the PS strategy. The LCOE increases alongside energy consumption until the overdesigned ESS provides the extra energy needed to avoid the excess of peak demand limits. Due to the additional ESS utilisation, the LCOE decreases for the two last cases even if the grid purchases increase. This means that, under the PS approach, the HRES is the optimum aiming at the port's economic feasibility and the CF diminishing. Regarding the HRES autonomy, both the LCOE and the energy savings are higher for the highest-autonomous systems. The RES LCOE is decreasing as the resources' availability is increasing. Similarly, the net grid purchases are negative (sales) for the enhanced resources.

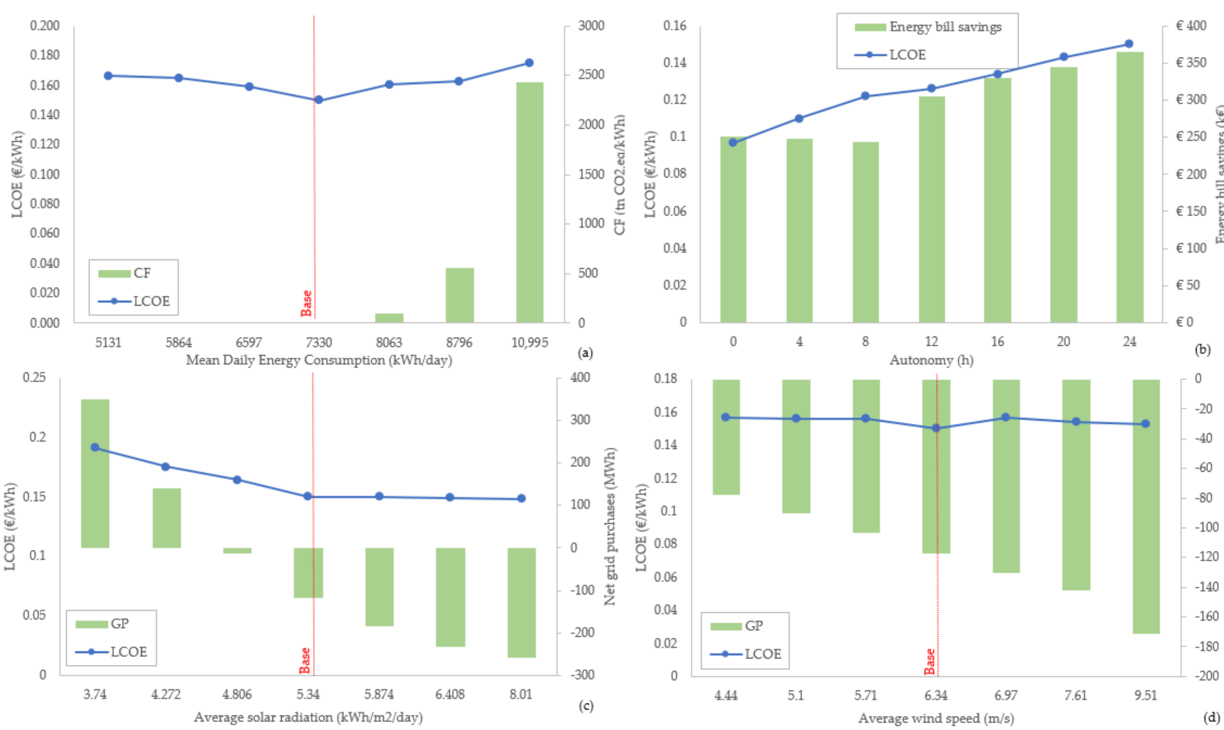

Figure 5.66. Sensitivity analysis for the four varying parameters under the CC strategy

For the non-NM cases, the proposed system of scenario 9 is ideal both in terms of CF and LCOE. In an unforeseen increase in demand, the LCOE will increase as the HRES will not cover the energy needs; the CF will be positive due to the grid purchases (Figure 5.66a).

As for the power supply's autonomy, as the autonomy gets higher, the energy bill savings are increasing, but the LCOE is also increased because of the higher initial capital needed for the extra ESS (Figure 5.66b). The PV penetration in scenario 9 is high, making the HRES highly dependable on the area's solar potential. Subsequently, if the solar radiation is reduced, the HRES cannot cover the total energy demand, resulting in grid purchases and GHGs (Figure 5.66c). Also, the impact on the LCOE is substantial for the decreases in solar potential; they are scarce if the potential is increased because of the zero-sell back rate of the excess energy. Since only one WT is suggested for the optimal case (Scenario 9), any alteration of the wind speed is scarce for the LCOE; however, the grid purchases are lowered as the wind potential increases (Figure 5.66d).

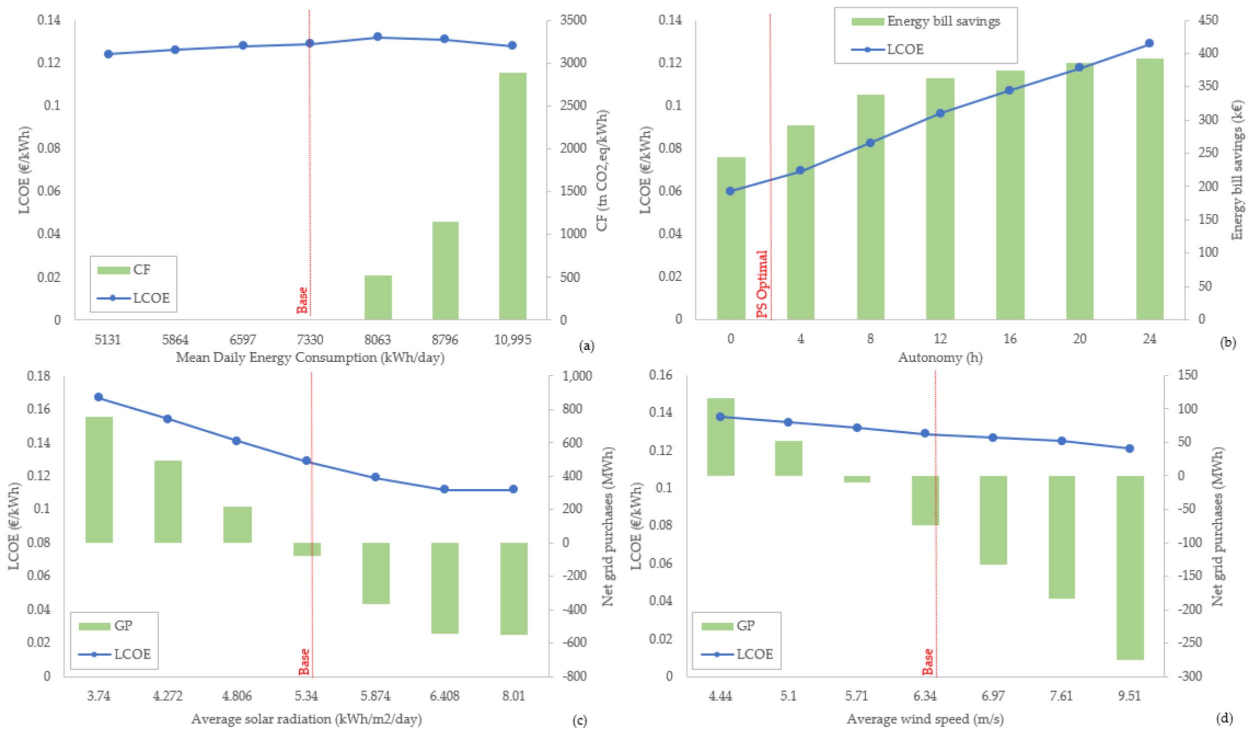

Figure 5.67. Sensitivity analysis for the four varying parameters under the PS strategy

After a certain point, as the energy demand increases, the LCOE decreases; the CF rise more sharply after this point (Figure 5.67a). Contrary to the previous case, the higher the power supply's autonomy, the less abrupt are the changes in the energy bill savings. Meanwhile, as autonomy increased, so does the initial required investment, leading to higher LCOE (Figure 5.67b). Finally, regarding the green potential of the area and how this affects the system's stability, it is observed that in this case, the impact of altering the solar radiation or the wind speed is similar to the HRES, due to the increased WTs number compared to the non-NM case (Figure 5.67c and Figure 5.67d). Lastly, as the green potential decreases, the less the RES energy output will be, leading to inadequacies in energy supply and, therefore, grid purchases and GHGs.

6 Conclusions

In this chapter, the main conclusions and the future recommendations of this thesis are presented and discussed. Each subchapter is inherently connected to each study area, and the last one is about the overall conclusions regarding the holistic nZEP concept.

6.1. Examining the past literature

Although ports tend to be similar amongst themselves due to their utmost goal of transporting passengers and goods, they are different and have distinct features. Based on their services and energy demand, the research team attempted to establish a typology and categorise ports into three (3) main categories. Meanwhile, there are no global key criteria for determining how ports could be energy independent, emission-free, or all-in-one, nZEP. The established typology offers the capability to generalise the study's outcomes to more than one port category after modest modifications proportionate to each port's unique characteristics. The high number of reviewed studies through the state-of-the-art process ensures that many viewpoints are included, and the prospect of nZEP is evaluated from many angles. After reviewing more than 300 research papers, a few conference proceedings, and reports, the most crucial literature's research gaps were identified. All the reviewed measures were analysed and evaluated, highlighting their pros and cons for future implementation and their economic or technological maturity, according to their cost-effectiveness and the expertise in each case. Port decision-makers can take advantage of this thesis literature review part as it is a structured, comprehensive, easy-to-use guide, providing solutions to most of the upcoming dilemmas. Researchers can be informed about the possible gaps and know where to focus their interests and attempts.

6.2. Forecasting the future energy port's demand for 2030

Moreover, the thesis investigates the reliability and ease of using various well-known **forecasting models** for the expected energy demand of a port for the year 2030, taking advantage of the acquired hourly 5-year energy demand data. Techniques such as simple linear regression, time series models as well as machine learning are exploited. The H-ANN model has a reasonably high R^2 (0.94) and satisfactorily fits the actual data. Nevertheless, its creation is still a complex process. The H-ML model has the highest R^2 (0.99) among the examined techniques, adapting quite satisfactorily to the actual data. However, high processing power is required. The H-ML model estimates that the port's annual energy consumption will be increased by about 54% compared to 2019. The results agree with the previous researches in the field of energy forecasting; ML models can be a valuable tool in the field of forecasting and long-term development strategy, as combined with the increasing computing power of modern computers, they become increasingly reliable and provide solutions to complex problems in a relatively short period. Also, according to a conducted statistical analysis, outdoor lighting is the most energy-demanding service of all the examined ports.

6.3. Renovating the port's outdoor lighting by implementing a SOLCS

Also, according to past literature, **lighting infrastructures** correspond to more than 15% of the total energy demand worldwide and are responsible for 5% of the global GHGs. Because of the great potential of integrating smart control systems into lighting infrastructures for indoor and outdoor spaces, several initiatives are presented in past research works, alongside various real-world applications that are already in use; the pilot projects are increasing.

The proposed SOLCS of this Thesis responds fast and accurately to any possible lighting conditions' alterations with a low computational load. Compared to the past literature, this system can operate at real-time conditions, computing almost immediately the required wattage of the luminaires according to any possible variation of the daylight illuminance. There are no prediction schemes or motives that may lead to inaccurate outcomes. Actual data are used for all the aspects of this study to ensure the reliability and the robustness of the outcomes and conclusions; the validation and the evaluation of the typology are based on actual measurements, ensuring high consistency and conclusions' safety.

As an overall outcome, energy wastes during the first, the last, and the late-night hours are diminished, leading to substantial benefits. Both the system's energy efficiency and lightning outcome are enhanced. This methodology leads to a 56.8% decrease in the port's lighting operations' annual energy consumption. This has economic and environmental benefits, as the total carbon footprint is reduced, and the yearly energy costs are also decreased. It is calculated that almost 10,000€ can be saved annually, alongside a 42.72 tnCO2eq reduction; the local electricity grid is also relieved. In a similar past research work conducted in Italy, it has been shown that more than 60% of the initially consumed energy can be saved by replacing the old luminaires with LED ones and by integrating smart dimming controllers [395].

6.4. Optimally sizing a port HRES to cover the energy demand and eliminate GHGs fully

As for the port's HRES optimal sizing and implementation, two different types of RES, two types of ESS, and two grid cases were examined, resulting in 35 possible scenarios. Therefore, 35 optimally-picked HRES are presented, of which four are figuratively demonstrated in the results section, picking the best option satisfying the financial prosperity, the GHGs diminishing and the social acceptance related to the port services. The significance of this assertion is being strengthened by the fact that the port, on average, needs 2.4MWh/day, which equals the daily energy consumption of almost 80 households.

As for the grid's NM cases, all the suggested HRES were feasible and realistic except for these incorporating the 48-h port's services autonomy by integrating the LA ESS. Indicatively, the LCOE ranges from 2.2 to 14.1c€/kWh, which are lower than the baseline (16.0c€/kWh). Also, the port's CF is eliminated, suggesting HRES emit from 38.7 to 73.8gCO_2,eq/kWh; the baseline CF equals 2250gCO_2,eq/kWh. The optimal-picked case among the candidate pool was the HRES of scenario 5 as it concurrently satisfies all the three criteria the research team has set; the LCOE is reduced by more than 50%, the CF is diminished to 90% less GHGs, and the social acceptance of the port is enhanced through the -at least 24h-autonomy of the port services.

Regarding the non-NM cases, the proposed HRES' LCOE range from 10.9 to 15.2c€/kWh for the feasible solutions, while the 24-h LA ESS cases have LCOE greater than the baseline due to the ESS high initial capital cost. On the other hand, the feasible scenarios' HRES CF ranges from 364.3 to 1639.9gCO2,eq/kWh, being lower than the baseline. Indicatively, the optimal-picked case on environmental terms is the HRES of scenario 28, which incorporates two types of RES (PV, WT) and VRFB ESS to provide at least 24h autonomy to the port services. The LCOE of this HRES equals 0.117€/kWh and the CF to 374.7gCO2,eq/kWh. Thus, the financial and the environmental financial and environmental outcomes of the non-NM case are worse than these of the NM cases, indicating the importance of the grid's NM functionality.

The grid's NM functionality enhances the ports' viability, credibility, and CF; the NM scenarios provoked substantial financial and environmental indexes (IRR, PP, LCOE, CF). It is indicative that the port's CF is decreased by more than 90% from the baseline state; ports can be turned into nZEP in a realistic and viable manner. The study's results are similar to other available studies for different infrastructures. Although there are adequate studies on optimally sizing an HRES, there are no studies regarding a port's operations. Also, no studies focus on all three aspects of sustainability, highlighting the innovative aspect of this research work.

6.5. Introducing the cold-ironing technique into a small Mediterranean port by examining the efficiency of a hydrogen-based HRES

Regarding the small-sized ports cases, they tend to use outdated technologies, commonly based on fossil fuel combustion, to meet their energy demands. Therefore, their operations harm the natural environment, causing severe aerial and noise pollution. This study aimed to examine several ways of upgrading the port of Adamas by embedding a green hydrogen system, making it an autonomous infrastructure, and minimising the GHG emissions produced, due to its operations, while ensuring that the proposed solution is economically viable and socially acceptable.

To accomplish this, actual data was gathered, and thirteen scenarios were simulated to compare different sensitivity cases. One primary sensitivity case was categorised into these scenarios: implementing CI and the probability of providing electric energy to berthing vessels. After simulating each scenario, a comparison was conducted; the optimal scenarios were chosen, either with or without the CIs integration. The two optimal solutions are based on the three sustainability aspects: economic viability, social acceptance, and reduction/minimisation of EF. Significant conclusions were reached after simulating each scenario.

Based on literature market data, every scenario, which was designed, proves the tremendous environmental benefit of installing a green hydrogen system in a small-sized port by eliminating its GHG emissions. Systems of scenarios 5 and 11 propose using PVs and WTs, as a more stable solution. As a result, the grid's participation in electricity generation is reduced. Nevertheless, the common opinion regarding the WTs is uncertain, and without a social research's conduction, these scenarios pose a significant risk. According to the peak energy load (systems of scenarios 6, 12), the design is also financially impractical, as the energy demand is not fixed in a port facility. The design of a system with an El that can fill the HT in only 8 hours (systems of scenarios 7, 13) is a viable option and proves to be the least power plant-dependent as the grid's participation in energy production is the lowest. The fourth and tenth scenarios's systems were deemed to be the optimum. The EF is minimised, and the grid generates only a tiny percentage of the system's energy load. At the same time, they offer the best economical solution since they significantly reduce the LCOE. Therefore, based on hydrogen ESS and CI, the renewable systems could be an example to emulate for small-sized ports.

6.6. Evaluation of two micro-grid energy dispatch strategies for a port HRES

Lastly, regarding the smart dispatch strategy, the impact of two dispatch strategies in a port's HRES is examined. Two grid cases are considered for a PV/WT/ESS HRES. Three different ESS types (LA, LI, and VRFB) are examined and evaluated, pointing out the most suitable. In total, the optimal HRES solution for 17 scenarios is identified.

The optimised techno-economic and environmental parameters of the study's results were assessed and discussed. In addition, the impact of several varying input parameters on the HRES was examined, such as wind speed, power demand charges, LI ESS cost, and WT cost. The suggested HRES is optimised to meet the actual load demand in every timestep, at the least NPC. The mean energy demand is 7330 kWh/day, and the peak demand is 533kW for the whole year. The current LCOE is 14.9 c€/kWh, according to the energy billing scheme.

The two dispatch strategies led to different outcomes for the suggested HRES due to their different energy usage goals. The PS provided better results for all the examined scenarios since it eliminated the power demand charges by sizing the system to serve this goal instead of delivering the maximum feasible renewable power. Indicatively, for the grid-connected HRES, the optimal solution for the 24-h autonomous HRES has an LCOE of 12.9 c€/kWh (20% less than the baseline) and a zero CF (100% less than the baseline case), providing the electricity grid with 74 MWh RES surplus energy due to the inadequate ESS energy capacity. Meanwhile, the optimal PS case's LCOE was 8.2 c€/kWh, incorporating 10-h autonomy. Unfortunately, there are not related studies to compare the study's results for the PS strategy; the proposed HRES in other applications presented similar findings regarding the CC strategy.

As for the grid-connected NM cases, the optimal-sized HRES had an autonomy of 10 h to cover the energy demand limits via RES and an LCOE of 8.0 c€/kWh (50% less than the baseline case). The LCOE of a 24-h autonomous HRES was 12.9 c€/kWh, the same as the grid-connected case. Consequently, the PS strategy incorporated even better outcomes for the NM cases. The study outcomes are reasonable and highly replicable according to the available past HRES-related studies for other infrastructures. However, there is low availability of port-based HRES studies.

As concerning the three ESS types, VFRB is the preferable one due to its higher cost-effectiveness than the other two. There were cases in which the LCOE of the suggested HRES with other batteries was lower than the VRFB. However, these scenarios were not economically optimal due to their higher initial capital cost. The most important aspect of the VRFB-based HRES was its 10-h autonomy when its competitors could support 4-h of autonomous power supply. Shortly, incorporating the actual energy billing scheme will promote this implementation, provoking similar outcomes.

6.7. Setting sail for the future of ports by introducing the nearly Energy Zero Port concept

Consequently, decisions and actions must be taken immediately to address the energy crisis problem by the competent bodies to comply with global and European rules to meet energy requirements with RES systems to address future sustainable development.

Smart lighting has the potential for advancing key research areas in energy-efficient buildings, human health, photobiology, telecommunications, and human physiology in our living spaces and workplaces. The future of smart lighting approaches is a multi-disciplinary research field. Consequently, the existing smart lighting systems need to be thoughtfully re-built to create a brighter future for lighting, inspired by the current research.

Concluding, this work also offers a thorough and well-established methodology and typology of examining the potential of converting a port to nZEP by firstly optimally sizing and integrating the optimal-picked HRES. The suggested typology is highly replicable and applicable in any port case regardless of its size and energy demands. The two main limitations of this study were that (a) there are no available studies on ports to compare the proper study's findings, and (b) other RES could not be examined due to the lack of resource data and actual costs.

Finally, the port's upgrade will bring substantial benefits for the port's surroundings, providing environmental, economic, and social euphoria. At the same time, the port's operations become more stable, thanks to the ESS or hydrogen energy storage technology's implementation, and thus, the port cities' permanent residents' energy demands would be satisfied throughout the year. Besides, the sustainable and stable port's function could be an additional factor for the selection of the port's surroundings as a place to be visited by tourists, contributing directly (costs of electricity as well as accommodation in the port) and indirectly (support of local businesses by visitors) to the island's economic prosperity.

The nZEP concept promotes an attractive infrastructure that uses almost explicitly green energy leading to zero GHGs, offering a critical helping hand to climate change mitigation. The energy transition from fossil-fuel energy generators to RES will also benefit the circular economy, enhancing the coexistence among ports and the surrounding port cities. A cleaner future for the mobility sector is imminent through the nZEP concept, which SEMS like the proposed one strengthens. It is indicative that the proposed HRES, with the suggested SEMS operation, achieve almost zero GHGs and an economically feasible investment towards sustainability, concurrently enhancing the port's services safety-of-supply through the 24-h autonomy. The ports' crucial role in the global GHGs emissions has been highlighted, indicating the importance of their transformation into innovative and energy-efficient infrastructures.

It is essential to mention that, in every aspect, the nZEP concept can be the connector for all those mentioned above. As it has already been mentioned, it incorporates a synthesis of different combinations of all the sustainable technologies towards an emission-free, energy independent, and contemporary infrastructure.

Lastly, this research work's findings should be used to create opportunities and guide worldwide port authorities, researchers, and developers to integrate RES into their studies.

6.8. Future recommendations

Various research gaps have been mentioned in this thesis regarding ports' sustainability and several relevant research fields. Nevertheless, the thesis has successfully filled some of these research gaps; however, the existing and several other areas regarding ports' sustainable development can be further examined in future projects. In conclusion, future researchers are to pay special attention to the following, concise fields of study:

6.8.1. Literature review

- More research is needed regarding the less mature smart techniques and technologies;
- There is a need to widen the range of studies regarding both the regionality and the size of the ports. The need to examine and evaluate sustainable measures and techniques for port infrastructures in Africa and the Middle East is more than obligatory;
- More studies are needed concerning the cooperation between port-related parties;
- The available research work has to be implemented, up taken, and tested into actual port conditions, evaluating the measures' actual applicability.

6.8.2. Energy forecasting models

- Further research on the part of forecasting models - use of other existing models
- Use of hybrid prediction models
- More and less-known RES, such as tidal and wave turbines, should be examined and implemented;
- Alternative green fuels such as biofuels should be used to cover energy needs, especially for replacing diesel engines;

6.8.3. Port's SOLCS

- To install sensors to various port's spaces to acquiring actual illuminance data;
- To apply this methodology to other infrastructures, such as university campuses,

villages, streets, etc.;

- To apply the system indoors, such as offices, to examine its effectiveness;
- To examine other more efficient luminaires.

6.8.4. Port's HRES

- More and less-known RES, such tidal and wave turbines should be examined and implemented;
- Alternative green fuels such as biofuels should be used to cover energy needs, especially for replacing diesel engines;

6.8.5. Hydrogen-based HRES and Cold-ironing

- To conduct a more thorough investigation regarding the Greek market' data for the hydrogen system's cost;
- Social research should be focused on public opinion, regarding RES and their social impact;
- To conceptualise more scenarios, including a greater variety of RES and ESS.

6.8.6. Ports smart dispatch strategy

- The PS dispatch strategy should be used in other case studies to examine their efficiency on different load demand profiles, i.e., houses, factories, islands, and other facilities that may have sudden peak loads throughout the day hours.
- An emission penalty could be modelled for the energy-demanding industries, leading to even better results.

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